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STUDY OF THE COMBUSTION CHARACTERISTICS
OF A NUMBER OF COAL WATER SLURRIES

by

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PROJECT: A STUDY OF THE COMBUSTION CHARACTERISTICS OF A NUMBER OF COAL WATER SLURRIES

TITLE: THE DETERMINATION OF THE COMBUSTION AND HEAT TRANSFER PARAMETERS OF FOUR (4) COAL WATER MIXTURES

FINAL REPORT

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SUMMARY

Seven commercial coal water slurries made with various coal types and particle sizes, have been tested on a 2.5MW thermal input scale in furnace conditions designed to simulate an oil fired boiler. Many designs of atomizers were tested, with three types being selected as suitable for CWS atomization. With the optimum type atomizers, the slurries were tested over a wide range of burner inputs and settings. All the slurries tested could be burned without a support flame, with total combustible burnout levels ranging from 95-99%. However, a very large spread in the rate of atomizing air for the different slurries was required to achieve these results, varying from 14% to 28% of the fuel flow. The slurries which could be effectively atomized with the lower atomizing air rates were also the slurries which could be burned effectively without air preheat and those which had the greatest turndown range.

From the slurry characteristics which were measured, it was not clear why such a great difference in the slurry atomization process for different slurries was found.

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NOMENCLATURE

A_o - input coal ash concentration

A_1 - local ash concentration

AD - axial distance (cm)

AFR - atomizing air/fuel ratio ($\dot{m}_{atm}/\dot{m}_{cws}$ (%))

Atm - atomizer

C_o - solids concentration (g/m^3_o)

CWS - coal water slurry

d - particle diameter (µm)

d_a - diameter atomizing air port (mm)

d_f - diameter fuel port (mm)

d_m - diameter mixing chamber (mm)

d_s - width of fuel injection slit for T-jet atomizer (mm)

D - burner throat diameter (mm)

Di - gun diameter (mm)

ERZ - external recirculation zone

FC - furnace coverage

hvb - high volatile bituminous coal

HP - horizontal position

HFO - heavy fuel oil

IM - internal mix atomizer

IRZ - internal recirculation zone

lvb - low volatile bituminous coal

L - Quarl length (mm)

m - mass flow rate (kg/h)

mvb - medium volatile bituminous coal

NG - Natural gas

P - pressure (bar g)

Q - heat flux to the furnace wall (kW/m^2)

R - radiative heat flux (kW/m^2)

S - Swirl number

$$S = \frac{\text{Flux of angular momentum}}{\text{Flux of axial momentum x burner throat radius}}.$$

SH - single hole atomizer

SR 1 - primary zone stoichiometry

$$SR\ 1 = \frac{\text{Secondary air + atomizing air + purge air}}{\text{Stoichiometric air requirement}}$$

T - temperature (^{o}C)

T_{CO_2} - carbon burnout of the coal based on the flue gas CO_2 concentration

T_x - total combustible burnout of the coal:

$$T_x = \frac{1 - A_o/A_1}{1 - A_o}$$

v - velocity (m/s)

α - quarl half angle

β - heat balance closure (heat removed by furnace cooling water plus heat contained by the flue gases divided by total thermal input)

γ - spray angle

ε - emissivity

λ - overall stoichiometric ratio

η_f - furnace efficiency (heat removed by cooling water/total thermal input)

μ - apparent viscosity (cP)

Subscripts

atm - atomizing fluid

sec - secondary air

tert - tertiary air

vol - volatile

Abbreviations concerning atomizer types are explained in figures 7, 8 and 9.

1. INTRODUCTION

1.1 BACKGROUND

The rising costs of fuel oil (HFO) over the last decade, together with potential oil shortages in the future, have led to a great deal of interest in coal-water slurries (CWS) as a replacement fuel for certain industrial applications. Several problems remain to be solved before CWS can become an economically and technically feasible replacement fuel in many facilities now firing oil. One major problem area appears to be difficulties with flame stability, particularly at lower combustion air preheat temperatures and with slurries prepared from low volatile coal. In some recent research on coal-water slurry some parameters have been identified as being important in CWS combustion, namely coal volatile content, particle size distribution, combustion air temperature and especially atomizer design.

However, the possible interactions between those parameters as well as other burner design parameters, such as swirl level, quarl design or atomizing fluid are not completely clear for these new fuels.

1.2 OBJECTIVES

The primary objective of the work reported here was to investigate burner design parameters in order to optimize the combustion of various coal-water slurries under furnace conditions simulating a wall-fired boiler. The burner parameters involved, quarl design, swirl level, primary zone stoichiometry, combustion air preheat as well as atomizer design and atomizing fluid rate.

The second major objective of this work was to provide information on the influence of coal type and CWS production process on the combustion of CWS. To achieve this second objective seven commercial slurries were fired. Both slurries made with the same commercial process but different coal types and the same coal type but different manufacturing processes were tested.

2. EXPERIMENTAL FACILITY

2.1 FURNACE

The IFRF number 2 furnace was used in this work. The furnace has dimensions of approximately 1.2 x 1.2 x 4.25m and is constructed of 17 water-cooled elements (see figure 1). Each element has an individual water meter and temperature monitoring on the input and output water flow in order to measure the amount of heat extracted from the flame as a function of axial distance.

The heat removal rate from the flame was varied by covering part of the water-cooled furnace walls with refractory. The furnace configuration used most of the time was 3/4 coverage, meaning the two side walls and the floor were insulated with refractory material (see also figure 1). In this configuration the nominal input of 2.5MW would yield a flue gas temperature of approximately 1000C with an associated heat extraction by the water-cooled element of approximately 50%, simulating the radiant section of a watertube boiler.

Another furnace coverage (FC) applied was 1/4 where only the floor was insulated. Also some tests were carried out in a completely water-cooled surrounding (FC = 0). The heat extraction efficiencies are 60% and 70% respectively for FC = 1/4 and 0. These two conditions are more severe than the 3/4 coverage and are perhaps representative of a cold start up or conditions in a small firetube boiler. The residence time in the furnace when firing 2.5MW is approximately 1.25 seconds.

2.2 EXPERIMENTAL BURNER

A schematic of the experimental burner is shown in figure 2. It is a circular burner with the fuel gun for the CWS situated on the axis. Surrounding the CWS-gun is an annular gas gun featuring an inner annulus for a purge air stream and an outer annulus for natural gas. The gas was injected through 36 holes of 3 mm with a 30^{o} angle with respect to the axis. (Natural gas injection was used for ignition and

support of slurry flames when needed). A close-up of the burner throat is shown in figure 3.

The secondary air stream is swirled by means of the IFRF movable block swirler giving a continuous variable swirl level (see figure 4).

The fuel guns and secondary air stream exit into a divergent quarl. The quarl half angle, α, was selected to be 35°. Earlier work [1] had shown that this quarl angle would give more flexibility regarding atomiser spray angles than a 25° half angle. Furthermore, it has been reported that wider quarl angles have a positive effect on the strength of the internal recirculation zone [2].

Also increasing the length, L, of the quarl is believed to have the same positive effect. A possible drawback of a longer quarl is increased potential for slurry spray impingement on the quarl's surface. In order to investigate the effect of quarl length two quarls were available with L/D ratios of 1.1 (quarl L) and 0.7 (quarl M) respectively.

Furthermore the burner has four tertiary air ports located around the quarl exit. An important consideration in interpreting the in-flame measurements is the orientation of the staged burner in the furnace. As shown in figure 1 the staging ports are located in the corners of the furnace and consequently measurements are executed in a plane in between the staging air streams.

The secondary air duct had a throat diameter D = 234mm. Inserts of 207mm, 194mm and 181mm could be placed to allow for increased throat velocities or maintenance of velocity when reducing primary zone stoichiometry.

The throat velocities of the secondary and tertiary air streams are shown in figure 5 as a function of primary zone stoichiometry (SR 1). The latter is defined as follows:

$$SR\ 1 = \frac{\text{Secondary air + purge air + atomizing air}}{\text{Stoichiometric air requirement}}$$

2.2.1 Atomizers

Several types of atomizers have been tested during these trials, all of which are of the twin fluid type.

The standard and divergent Y-jet atomizers had spray angles of 20°, 25° or 30° (half angle). The number of exit holes was either 6, 8 or 10. Figure 6 shows the two types and the characteristic dimensions of each atomizer individually. The standard Y-jet was designed following the criteria as proposed by Mullinger and Chigier [3].

The T-jet atomizer was a new design. Here the fuel flows into an annular space surrounding the atomizing air jet completely. It was believed that a better distribution of the CWS through the mixing chamber was achieved (see figure 7). Only T-jets with a 25° half spray angle and 8 or 10 exit holes were constructed.

The Internal Mix atomizers (figure 8) were also constructed with 20°, 25° and 30° spray half angles.

The Single Hole atomizer was a modified version of a design originally used by Babcock & Wilcox [4]. The CWS enters the atomizer axially through a nozzle. The atomizing air enters the mixing chamber through 6 holes around the circumference. Two versions were available with radial and tangential air injection into the fuel stream. The length of the mixing chamber could be changed by applying a cap on top of the atomizer (see also figure 8).

2.3 CWS HANDLING SYSTEM

The CWS storage and handling system is schematically shown in figure 9. The slurries were stored in $26m^3$ road tankers. Recirculation of the CWS when required for stability was achieved by two agitators (157rpm) inserted through the manholes. More recirculation could be

generated via extra Mohno pumps operating at a variable rate of 2 - 9 m^3/h. A Mohno pump with a variable speed supplied the CWS to the burner. A dual filter set was incorporated in the burner feed line. The filter consisted of 3" diameter screens with apertures of 1.4mm. An indication of the state of the filter in use, with regard to blockage, was given by means of a differential pressure gauge set across the filter units. Two flow meters were tested during the experiments; a magnetic flow meter and a Micro Motion mass flow rate meter. The former did not perform satisfactorily; the output signal fluctuated and the mean value did not agree with the actual flow rate. However the Micro Motion meter proved to be capable of measuring CWS mass flow rates accurately and was therefore used throughout the trial.

2.4 FUELS

In order to achieve the two objectives as stated in 1.2, seven coal water slurries were acquired from four different manufacturers. The coal types (mainly volatile matter content) for each slurry was selected such that the seven CWS's labelled A through G would construct the matrix shown below.

		Manufacturer			
		I	II	III	IV
Coal	Low volatile	B			
	Medium volatile	A	F		
	High volatile	D	C	E	G

TABLE 1 - COAL WATER SLURRY TEST MATRIX

The volatility of the coals indicated by low, medium and high refer to contents of smaller than 20%, 26% - 29% and greater than 30% volatile matter respectively on a dry ash free basis.

All slurries were commercially produced mixtures. Therefore, the chemical package in the slurries as well as the coal particle size distribution were determined by the production process of the manufacturer. One of the slurries was made from a beneficiated coal, CWS-E, and one from partially beneficiated coal (CWS-G).

Table 2 lists the proximate and ultimate analyses of the coals, the coal content and viscosity of the slurries.

The particle size distribution of the coals are shown in figure 10.

Heavy fuel oil was fired in the same configuration to compare heat transfer characteristics.

The analysis of the HFO can be found in table 3. Table 3 gives also the composition of the natural gas which was used in a few cases for support of CWS flames.

2.5 INSTRUMENTATION

Standard IFRF techniques were applied for flue gas and in-flame gas and temperature measurements.

Information for most of the equipment is given in various IFRF publicatons [5].

o For the gas analysis the following analysers were used:

O_2	- paramagnetic analyser
CO_2	- IR analyser
CO	- IR analyser
NO_x	- chemiluminescent analyser
SO_2	- UV photometric analyser

o Flue gas solid samples were collected in a special probe. Figure 11 shows the schematic of the probe. For in-flame solid samples the standard probe was applied using ceramic filters. See also figure 11; a complete description is found in [6].

- The aerodynamic flow patterns were determined with the two-holes "Hubbard" probe and the newly developed "Schreier" probe. The latter consists of a water-cooled probe with a ceramic shield at the end (see figure 12). In the shield a flow of acetylene and compressed air are mixed. The mixture produces a small flame at the open end of the shield. Outside the furnace the flame will be directed along the probe axis and eventually slightly upwards due to buoyancy effects. However, when inserted into the furnace the acetylene flame will be deflected by the gas flow in the furnace. In this way the boundary between forward and reverse gas flow can be accurately determined as long as the brightness of main flame does not exceed that of the acetylene flame. In practice with the relatively non-luminous CWS flames the "Schreier" probe could be used in the flame with the same accuracy as the Hubbard probe. However in the direction towards the flue duct, the sensitivity of the Hubbard probe generally limits measurements up to AD 50. The "Schreier" probe proved to be sensitive enough to determine gas flow directions up to AD 160.

Total incident radiation was measured with the narrow angle probe (view angle 1^{o}). For a complete description see [5].

2.6 INPUTS

The 3/4 coverage of the furnace with refractory bricks was the condition in which all CWS's have been fired. For a few cases refractory was (partially) removed to study the effect of heat extraction on the combustion.

The nominal thermal input was 2.5MW with a combustion air temperature at the burner of 300C. Also some test runs have been carried out using ambient temperature combustion air. In case of reduced refractory coverage in the furnace the combustion air temperature was increased when necessary for CWS ignition without gas support.

Air was used as atomizing fluid; a limited number of tests were carried out with steam for comparison. The steam temperature was varied from 170 to 300C.

3. EXPERIMENTAL RESULTS

The experimental phase was divided into two parts; in the first part the influence of burner parameters was investigated. This work was carried out using one coal water slurry only (CWS-A). The second part involved the other six CWS's. Each of these were fired for 3 or 4 days, in order to evaluate the slurries atomizability and combustion performance.

The input and output data for all the flames fired in this trial can be found in tables 4 - 12. The flame numbers, which appear in the tables and figures as well as in the text of the report are composed of 2 letters and 2 numbers (e.g. AL-234-12) The first letter identifies the CWS (table 2); the second letter relates to the quarl used; L = long quarl and M = medium length quarl, see figure 2. The number after the first dash is the diameter of the secondary air insert in mm. The last number is a serial number separating flames with different swirls, staging levels, atomizing air rates etc.

In general the CWS flames produced with optimized burner conditions ignited well back in the quarl, in most cases almost immediately upon leaving the atomizer when using the burner unstaged. The flames were relatively transparent and the visible flame length typically extended about 0.3m downstream of the quarl. When the burner was run under staged conditions the flames would be longer and in general more opaque. With all flames, large agglomerated particles were observed, but the number of these particles varied greatly with slurry type and the atomizer and atomizing air rate (see also photographs 1, 2 and 3).

In addition to visual observation, flames were characterized by their burnout. The burnout has been calculated by two different methods. The burnout labelled as T_{CO_2} is based on the CO_2 concentration in the flue gases and represents the carbon burnout. This method

requires an accurate knowledge of the input mass flow rates of the air and fuel streams. Furthermore it assumes that there exists no inleakage of air into or gas out of the furnace. The second burnout parameter, T_x, using standard ash tracing techniques represents total combustible burnout. The value of T_x is calculated from the formula:

$$T_x = \frac{1 - A_o/A_1}{1 - A_o}$$

where A_o is the ash content in the input coal and A_1 the ash content in the solid sample collected in the flue gas duct.

When firing pulverized coal T_x is normally used for the burnout. It was experienced that with CWS firing more care is required in both collecting and interpreting of the solid samples.

The reason for this is the existence of large agglomerated particles ($\sim$ 250 µm) in CWS flames. These agglomerates, formed during the atomization, were found with all slurries although the amount and size varied considerably for the various CWS's, the atomizer type, and atomizing air mass flow rate.

These large agglomerates will either drop out on the furnace floor or be carried over with the flue gases. The fraction that drops out is dependent on burner input, such as primary zone stoichiometry and swirl. These input conditions, especially the swirl level will also influence the radial distribution of the large particles in the flue duct. Since these large agglomerates are burned out to a lesser extent than the fines and can form a considerable fraction of the total solids mass flow rate, they are important in determining burnout levels. For a few selected flames solid samples were collected at various radial positions in the flue gas duct (see table 13). Flames with high swirl levels, e.g. AL-234-32, AL-234-33a and EL-234-13, showed high solid concentrations near the wall and low concentrations in the centre of the flue duct. However, flame GL-234-22, S = 1.44, had a concentration profile which was flat across the duct. A low swirl flame, AM-234-14 with S = 0.47, had the maximum

concentration in the centre of the flue duct.

3.1 BURNER PARAMETER ASSESSMENT-CWS A

3.1.1 Atomizer evaluation

During the course of the experimental work all the atomizers as described in paragraph 3.2.1 were tested with air as the atomizing fluid. However, not all the types and versions were available from the beginning of the trial. Some were designed and manufactured during the trial, the designs being based upon experience gained in the early part of the experiments. Initially the standard and divergent Y-jet (only the six-hole versions), the internal mix and the single hole atomizers were available. During the firing tests of CWS-A the eight-hole versions of the standard and divergent Y-jet were made. The CT-8 atomizer was designed in the time interval in between CWS-C and CWS-D test period. The 10-hole versions become available at the start of the tests with CWS-E.

Test firing with the internal mix and single hole atomizers proved that these types did not perform satisfactorily. The internal mix atomizers had a strong tendency to block. The apparent cause of the blockage was that the slurry would partially dry during the primary atomization inside the cavity. Thus large agglomerated particles would be formed and these would not pass through the exit holes.

The single hole atomizer would not allow a stable flame to be established without gas support. The reason for this problem did not appear to be a result of poor atomization, but more a result of the droplet spray penetrating completely through the internal recirculation zone centered on the burner axis. Consequently hot gases produced from combustion of the CWS would not be efficiently returned in the IRZ.

A short test was carried out with a rotary cup atomizer. The atomizer unit was a standard 3.2MW oil atomizer for which the housing had been changed in order to fit the experimental burner. The firing tests were not succesfull. A possible explanation for the bad atomizing

performance is that the optimum geometry for oil is not the best configuration for CWS. A shorter cup with a smaller diameter and perhaps a larger taper angle may give a better performance.

The performance of the standard and divergent Y-jet and T-jet atomizers were satisfactory. Comparison of two six-hole standard Y-jets with different hole diameters, CY-6 and CY-6L, showed the one with the smaller dimensions (CY-6) to perform better.

The optimum (total) spray angle (γ) for these types of atomizers was found to be a 50^{o} angle. This angle matches the droplet spray with the aerodynamic flow pattern such that the droplets initially travel through the IRZ and later into the forward flow. In this way the necessary heat to evaporate the water and to heat up to coal particles is supplied by the IRZ; somewhat further downstream the higher oxygen availability required for a rapid combustion process is given in the forward flow region. All the data given in this report for the Y-jet or T-yet type atomizers were achieved with a 50^{o} spray angle.

As regarding the number of exit holes in the atomizer it appeared that the eigth-hole versions tended to give better results compared to the six-hole atomizers. This was clearly observed when more severe combustion conditions were applied, such as reduced furnace insulation.

The ten-hole atomizers gave in general a comparable performance to the eight-hole type. However, with the ten-hole versions the CWS spray had to be carefully matched with the aerodynamic profile by means of the gun position. If the gun was not in the optimum position the flame appearance was poor and asymmetric or the flame would even extinguish. This phenomenon could be caused by the individual CWS jets emerging from the atomizer and interfering with each other.

With four of the slurries steam was also tested as the atomizing fluid. In all cases steam atomization was inferior to air atomization. Visually this could be seen as a large number of agglomerated particles in the furnace. These agglomerates would

impinge on the furnace walls resulting in a large amount of coal burning on the furnace floor. The flame appearance was poor with rather late ignition; the ignition front was located close to the quarl exit plane. Often staging of the combustion air was necessary for a quarl stabilized flame and the steam consumption would be as high as 30% of the CWS mass flow rate.

In figure 13 the burnout data from air and steam atomization are compared; the T_{CO_2} burnout values are the maximum values achieved with air and steam atomizaton for slurries A, B, E and G. The top diagram shows the results for CWS-A, E and G when fired in the nominal furnace condition) (FC = 3/4). While air atomization gives burnout of 96-99% the values with steam vary around 85%. CWS-A was also fired with saturated and superheated steam. The increase in steam temperature from 170C to 300C resulted in a rise in burnout from 83% to 92%. In case of CWS-G the steam temperature was 285C giving T_{CO_2} = 88% and for CWS-E the values were 235C and 85% burnout.

Firing a coal water slurry under more severe conditions resulted in a large increase in the difference in flame performance shown by the two atomizing fluid media. In the furnace configuration with only the floor insulated (FC = 1/4) CWS-B was fired with gas support. With air atomization coal burnout levels of 80-94% were obtained, depending on the primary zone stoichiometry. With steam as the atomizing fluid the maximum burnout was only 46% (see also figure 13).

The reason for the poor results using steam atomization is not quite clear. Two possibilities for its failure are plausible, firstly that the steam mixing with the cold slurry is condensed and secondly the slurry mixing with the hot steam is partially dried.

In order to test for these effects CWS-G was fired using hot atomization air (flame GL-194-4). The temperature was raised to 185C and over this range no change was seen in the atomizing performance. This is in agreement with the results of Borio et al [7]. The burnouts of flame GL-194-4 were 86% (T_{CO_2}) and 83% (T_x) respectively. This appears to be low but it probably resulted from the fact that the maximum atomizing air mass flow rate was only

76kg/h, corresponding to AFR = 21%, due to the increased pressure drop in the heater and in the atomizer due to the larger gas volume; typical values of AFR were 26-28% for good combustion of CWS-G (see also paragraph 3.7).

From this experiment it may be concluded that steam condensing when brought in contact with the slurry is a more likely reason for the poor performance of steam, than partial drying of the slurry.

To select an optimum atomizer from the various standard and divergent Y-jets and T-jet atomizers is rather difficult as their performance was dependent on the slurry type. With the nominal input conditions, 300C air preheat and 3/4 furnace coverage and using quarl L, a flame stabilized back in the quarl could be achieved without gas support with any of these atomizers. When the slurries were fired under more difficult conditions, such as with cold combustion air or without furnace insulation, or when the amount of atomizing air was reduced, then some atomizers had a clear advantage over others. The atomizer that gave the best performance over the widest range of slurry types and burner parameters was the eight-hole T-jet.

3.1.2 Influence of quarl length

The effect of quarl length was investigated using CWS-A. The two quarls used are shown in figure 2. Both had the same quarl half angle (35^{o}). The quarl length differed giving L/D ratio's of 1.1 and 0.7 for quarl L and M respectively.

However, when changing quarls the ratio of the furnace quarl exit diameter to the furnace diameter changes also. This may well have a large effect on the near field aerodynamic flow pattern [8].

In the cases of 3/4 furnace coverage with refractory material, flames fired through the long quarl could be stabilized with swirl levels from 0.47 - 2.1. Staging levels of 0.8 up to baseline condition (SR1 = 1.2) gave good stable ignition for flames AL-234-1 to -6.

When using the medium length quarl, the non-staged flame did not stabilize in the quarl. Increasing the swirl level up to S = 2.1 brought the ignition front back to 10cm downstream of the quarl exit plane. When going over to staging the combustion air the flames were quarl stabilized; the optimum swirl level was equal to the maximum achievable, i.e. S = 2.1.

The minimum secondary air temperature for self sustaining flames with the medium quarl was 220C. With the longer quarl, unsupported flames could be fired with ambient temperature combustion air, flame AL-234-5 (see also figure 14).

Apparently the residence time in the quarl as determined by the quarl length has a significant influence on flame stability under more severe operating conditions (non-staged flames or cold combustion air).

This is even more evident for the case with higher heat extraction rates from the flame, i.e. a furnace coverage equal to 1/4 or 0. Although, for FC = 1/4, the difference in minimum secondary air temperature for unsupported combustion for the quarls L and M is smaller, 300 and 360C respectively, the operating conditions were less restricted for quarl L.

The medium quarl gave only stable flames at SR 1 = 0.8 and a swirl equal to 0.47. The burnout levels were in the high eighties, T_{CO_2} = 90% and T_x = 85 - 89% (flame AM-234-14). For the long quarl, T_{CO_2} varied from 91 to 98% and T_x was in the range 88 - 96% depending on SR 1 and swirl (flames AL-234-22 to -34).

In a completely unlined furnace (FC=0) using the medium quarl the minimum air temperature was 380C. The fuele had a very low burnout, operating at SR 1 = 0.8 and S = 0.47 the T_{CO_2} increased from 80% at 388C to 93% at 407C and further to 97% at 420C. These flames were achieved using the CY-8 atomizer. The six-hole versions did not give stable flames.

For quarl L the minimum combustion air preheat level was 340C for FC = 0. Flames could be stabilized at swirl levels from 0.47 - 2.1 and staged and non-staged air inputs. The atomizers used were CDY-6, CY-8 and CDY-8 (flames AL-234-11 to -21).

Summarizing the results obtained with CWS-A for the two quarls it was found that the longer quarl gave better results over the widest range of burner inputs and furnace conditions. The longer residence time in the quarl and a strong IRZ [7] are clearly beneficial for CWS combustion. Quarl L was therefore used for the firing tests of the other sluries.

3.1.3 Primary zone stoichiometry

Staging of combustion air can be applied, apart from NO_x reduction purposes, to increase flame stability for low reactivity or slow burning fuels. In general lower mass flow rates of secondary air will dilute the heat generated to a smaller extent and result therefore in higher temperatures in the primary zone. However, the reduced oxygen availability in the early flame can have a negative effect on the final burnout.

In figure 15 radial temperature traverses, as measured at a distance of 5cm from the quarl exit, are plotted. The three diagrams give temperature profiles for a staged and a non-staged flame for three different swirl levels.

The minimum temperature in the radial traverse locates the position of the forward secondary air flow. The staged flames give higher values for this position as there is less mass flow of secondary air. The differences between staged and non-staged flames reduces with increasing swirl. For a swirl level of 0.47 the minimum value is very low, 750C for the baseline flame, as a result of slow mixing. The temperatures in the IRZ of the staged and non-staged case are equal.

For the 0.9 swirl level staging of combustion air yields peak temperatures which are approximately 100C higher.

At a swirl level of 2.1 the mixing and external entrainment rate is very high resulting in almost identical profiles for the staged and non-staged flame. Also the complete temperature fields for both flames are similar. In figure 16 diagrams B and C show the isotherms for these flames. The staged flame shows somewhat higher temperatures in forward flow region near the furnace wall. However on the axis the temperatures are lower.

For the S = 0.9 case figure 17-B shows the burnout, T_{CO_2} and T_x, for the staged and non-staged flame. Although the former had significantly higher (peak) temperatures the burnout is lower compared to the baseline flame. Apparently the reduced oxygen availability in the primary zone and possibly also further downstream in the furnace caused by slow in mixing of the tertiary air stream has a negative effect. The necessity for quick mixing of tertiary air shows from the analysis of solid samples collected at AD 60 for two non-staged flames with swirl levels of 2.1 and 0.9, flames AL-234-8 and AL-234-2. The burnout, T_x, at HP 80 and HP 100 has yielded 70% and 54% for the high swirl flame and 57% respectively 54% for flame AL-234-2 (S = 0.9) . The combustion has already proceeded to such an extent that when the staging air would not supply the additional oxygen the combustion rate would drop off because of the low partial pressure of oxygen.

In figure 18 the burnout data for the FC = 1/4 case are compared. For the furnace condition without any insulation (FC = 0) the effect of staging on the radial temperature profiles at AD 5 can be seen on the left hand side of figure 19. On the right hand side the traverses for FC = 3/4 are shown for comparison. The burnout as a function of SR 1 for FC = 0 shows the same trend as for the FC = 3/4 case (see figure 17A).

When firing a CWS made with a medium or higher volatile coal, and when the heat extraction rate from the flame is not too great (FC = 3/4), then an acceptable ignition performance can be achieved without staging the combustion air. If the combustion air is staged then a decrease in the carbon conversion efficiency is possible.

When burning a less reactive slurry or firing under more difficult conditions, then staging of the combustion air can increase the early flame temperatures and consequently improve the ignition performance.

The effect of staging on the NOx emissions is described in section 3.9 and shown in figures 55 and 56.

3.1.4 Swirl

The major source of ignition for a type 2 coal water slurry flame is the reverse flow of gases in the internal recirculation zone (IRZ). The minimum swirl level should therefore exceed that value which estabilishes an IRZ. With the long burner quarl a minimum swirl level of around 0.4 was required.

The effect of increasing the swirl level on the flame was to shorten the flame length with an increase in combustion intensity in the quarl. For some cases, usually the more severe conditions with regard to ignition and flame stability e.g. reduced furnace insulation, visual observation indicated that an optimum swirl setting existed, beyond which the combustion intensity in the primary zone would decrease.

As can be seen in figure 20, the temperatures in the IRZ are reduced with increasing swirl. The radial temperature profiles on the left hand side of figure 20 show this effect for the uninsulated furnace. The optimum swirl for that case was approximately 1.0. With this swirl the recirculated gases in the IRZ have reached a low temperature (1100C); a further increase in swirl and even lower temperature in the IRZ would not return enough heat to the root of the flame. Consequently evaporation of the water and heating up of the coal would take too much time and the flame would extinguish.

The second set of temperature traverses show that for FC = 3/4 the temperatures are 150 - 250C higher compared to the FC = 0 case, even with secondary air temperature of 320C as opposed to 450C which was required for the unlined furnace.

For the FC = 1/4 case the complete temperature fields are shown for swirl levels of 0.9 and 2.1 in figure 21. The higher mixing intensity of the latter results again in lower temperatures in the IRZ. The increase in mixing can also be observed from the radial gas concentration profiles at AD 5 (see figure 22).

In general, moderate swirl levels, about S = 0.9, were found to give the best combustion performance. The increased mixing rate associated with high swirl (>1.0) particularly between the secondary air and external recirculation gases was found to decrease flame and IRZ temperatures.

When flame temperatures are cold, T<1200C, as when using ambient combustion air, then the increased external entrainment rate of hot products associated with high swirl, S>1.0, can aid ignition.

3.2 CWS-B

Slurry B was made from a low volatile bituminous coal (18.7% d.a.f.) and had the same particle size distribution as the baseline slurry A.

The flames produced with this slurry were very transparent; also the visual flamelength was very short, sometimes not even extending out from the quarl. This slurry proved to be much harder to atomize than CWS-A. The operating range for the atomizing air rate was 22 - 30% of the CWS mass flow rate. Large agglomerates were found in the flue gas solids samples indicating a poorer atomization. Also because of the low volatile matter content the burnout did not approach the values as achieved for CWS-A. Figure 23A shows the burnout as a function of the atomizing air quantity.

The maximum burnout achieved was around 96% (T_{CO_2}) using a 29% atomizing air to fuel ratio. Reducing the atomizing air mass flow rate yielded an increase in large agglomerated particles and an accompanying reduction in burnout.

The eight-hole versions of the standard and divergent Y-jet atomizer proved to be superior to the six-hole types. All CWS-B flames were

therefore fired with eight-hole atomizers. Furthermore the divergent type was somewhat better than the standard Y-jet.

In figure 24 A and B isotherms are shown for flames with an CY-8 atomizer and 26% atomizing air and a CDY-8 atomizer with AFR = 24%.

Although the temperature fields are very similar the CDY-8 gives higher temperature zone along the furnace wall. This is also approximately the area through which most of the coal particles pass. The burnout of the CDY-8 flame was also higher, 92% versus 85% for the CY-8, in spite of a higher AFR for the latter.

Figure 24C gives the temperature field for a flame with SR 1 = 0.8 and even more atomizing air using a CDY-8 atomizer. Both the reduction in secondary air mass flow rate and the increase in atomizing air rate cause the temperature levels to increase; the burnout was 94%.

In figure 23B the effect of primary zone stoichiometry on the burnout is shown. The curves representing swirl levels of 0.9 and 2.1 have a maximum of approximately 96% burnout for SR 1 = 1.0. The burnout drops off significantly when increasing SR 1 to 1.2; values of approximately 88% were then measured. Figure 23B also shows that a swirl level of 0.9 gives a somewhat better performance than S = 2.1.

In order to achieve high burnout levels for CWS-B, staging of the combustion air is helpful. Also an increased atomizing air rate gave higher burnout levels.

It was also unsuccessfully attempted to fire this slurry with combustion air at ambient temperature. The minimum temperature for self sustaining flames in the 3/4 furnace coverage case was 260C.

A limited number of tests was carried out in the furnace when only the floor was covered with refractory material (FC = 1/4). In that case the minimum air temperature for unsupported ignition was 370C (see also figure 14). However, the flame was only stable at SR 1 = 0.8 and a swirl level of 0.9. The burnout for this condition was only

75% (T_{CO_2}). For the nominal air preheat (300C) the gas support requirement for ignition was investigated. This amount was dependent on the swirl level; for S < 0.9, 0.3MW NG was needed and 0.45MW was required at S = 2.1.

The burnout for these CWS/NG flames was rather poor, T_{CO_2} , ranging from 77% up to 94%.

In figure 25 A and B the effect of gas support on the temperature fields can be seen. An increase from 0.3 to 0.5MW of NG support yields significantly higher temperature levels throughout the near field of the flame. The burnout increases from 83% up to 88%. Diagram C in figure 25 shows the isotherms for a high swirl case. The intense mixing reduces the peak temperature in the internal recirculation zone to 1140C; consequently the burnout is very low 77% (T_{CO_2}).

In this furnace condition (FC = 1/4), a 3 : 1 turndown of the 1.85MW CWS/0.5MW NG was executed (flame BL-234-10). The burnout for this reduced load case was 71%.

3.3 CWS-C

Slurry C produced by manufacturer II was made from a high volatile bituminous coal (30.7 % d.a.f.). The particle size distribution was coarser than the baseline slurry 79% < 75 µm, see figure 10.

This slurry showed very good handling properties regarding storage and pumping. However, it was rather difficult to atomize. In the nominal furnace condition with the side walls and the floor covered with refractory bricks (FC = 3/4) and 300C secondary air preheat it was very difficult to achieve an unsupported CWS flame. Large agglomerated particles were always observed with this CWS. The amount of agglomerates was dependent on the atomizing air quantity.

Typical values for the atomizing air rates were 23 - 30%. Figure 26A shows the burnout as a function of the atomizing air rate. The standard eight-hole Y-jet was superior to the divergent Y-jet with respect to achieved burnout and atomizing air consumption.

Figure 26B shows the T_{CO_2} burnout as a function of primary zone stoichiometry for two atomizing air ratios. The higher AFR value (28%) has an optimum SR 1 around 1.0. For lower AFR (24%) the best value is in the range of 0.8 - 0.9.

The flame temperatures for this CWS were rather low, peaking at 1280C. In figure 27 the isotherms are shown for flame CL-234-27, which had SR 1 = 1.0 and AFR 29%.

Also some test runs were carried out with CWS-C in a furnace condition with only the floor covered with refractory (FC = 1/4). Stable, self sustaining flames could not be achieved without gas support. At an air preheat temperature of 400C, 0.05/0.1MW of natural gas was required; this is equivalent to 2-4% of the fuel thermal input. The resulting flame was still rather poor. Further tests in this furnace condition were executed at the nominal preheat level of 300C; the fuel thermal input was 1.85MW CWS-C and 0.5MW NG. Using the 207mm secondary air insert the resulting burnouts were very poor; T_{CO_2} = 52 - 74% (flame CL-207-1a to -3b). The highest burnout was reached with a primary zone stoichiometry of 0.8 and a swirl level of 0.8. The secondary air velocity was in this case 34m/s. When the 234mm diameter secondary air duct was applied to reduce V_{sec} to 26m/s, some improvement was achieved. Flame CL-234-1 had 83% T_{CO_2} and 86% T_x burnouts. The optimum input conditions was again SR 1 = 0.8 and S^x = 0.9. As can be seen in figure 27 the temperature levels in the flame are rather low apart from the small zone near the quarl exit where the gas combustion takes place.

3.4 CWS-D

Slurry D was also produced by manufacturer I. Made with a high volatile bituminous coal (35.9% d.a.f.), it had a slightly coarser particle size distribution than the two other slurries from this producer; CWS-D had 88% < 75 µm. The apparent viscosity as measured by a Haake viscosimeter was relatively high, 1830 cP at 100 s^{-1}.

The atomizability of this slurry was comparable to that of CWS-A. Figures 28A and B shows the burnouts, T_{CO_2} and T_x, versus the

atomizing air quantity for two atomizer types. The CT-jet, which was not available when slurries A, B and C were fired, showed a remarkable improvement over the eight-hole Y-jet. Burnout levels were as high as 98-99% with an AFR ∿ 16% compared to ∿ 93% for the CY-8 atomizer. Apparently the better distribution of CWS entering the mixing chamber of the CT-jet improved the atomizing performance for this slurry.

The dependence of the burnout on the primary zone stoichiometry is shown in figure 28C. This slurry seems to have an optimum SR1 value around 1.0; the burnout for the baseline flame (SR 1 = 1.2) is only 94-95% as opposed to 98-99% for SR 1 ∿ 1.0.

The isotherms for a baseline flame (SR 1 = 1.2) are shown in figure 29. Also the boundary between the forward and reverse gas flow is indicated as determined with the Schreier probe.

The internal recirculation zone was very large, approximately 1.3 meter long and 0.65m wide. This resulted in a fairly narrow area for the forward flow, approximately 20cm wide in a horizontal plane through the burner axis. There was no measurable external recirculation in that horizontal plane, apart from a small eddy very close to the furnace front wall (the size of this eddy could not be determined accurately with the Schreier probe). In-flame gas concentration measurements resulted in the isolines for oxygen and carbon dioxide as shown in figure 30.

The combustion results using ambient temperature combustion air are collected in figure 31. Diagram A shows that high T_{CO_2} values (97 - 99%) were achieved with 15-20% atomizing air which means that the atomizing air rate does not need to be increased when going from 300C preheat to ambient temperature air. However, the swirl level needs to be adjusted to 2.1 for good stable flames. Visually the effect of absence of preheat was to be seen as a somewhat delayed ignition of the coal but the ignition was still well within the quarl.

Figure 29 shows the isotherms of flames with and without air preheat. With cold combustion air the peak flame temperature is 1290C, a reduction of 160C compared to a combustion air preheat of 300C. In the case of cold combustion air there was a difference in performance of the various atomizers. The eight-hole T-jet proved to be the most successful (see also figure 31C).

3.5 CWS-E

CWS-E was made of a beneficiated Nova Scotia coal; the ash content was 1.46 %. The volatile matter content was the highest of all coals used in this trial 37.5% (d.a.f). The coal loading and the viscosity were relatively high, respectively 71.7% and 1420 cP at 100 s^{-1}. The particle size distribution of the coal showed a rather different curve compared to the other six slurries. It contained less fines (72% < 75 µm), but also less larger particles; see also figure 10.

The atomizability of CWS-E was good; comparable or even better than CWS-A and CWS-D. Good combustion performance, 97-98% burnout, was achieved with 14% atomizing air. Below this level the burnout decreased. However, 10% atomizing air gave still a stable flame (T_{CO_2} = 85%). Figure 32 A shows the trends for various atomizers.

In the range of 13 - 16% AFR there was not much difference in performance of the CDY-8, CDY-10 and CT-8 atomizers.

Figure 33 gives radial temperature profiles at AD 8 for three atomizer types at two swirl levels. The temperature levels in the IRZ are in all cases high, 1300 - 1400C, and the traverses are similar for the different atomizers.

The change in swirl level from 0.9 to 2.1, did not change the temperatures in the centre part of the IRZ at AD 8; only the peak levels at the interface between forward and reverse gas flow (HP 90) are evened out due to the increased mixing resulting from the higher swirl. Also the burnout did not change with swirl (figure 32B).

The effect of atomizing air rate on the temperature level at AD 8 can be seen in figure 34. The profiles for 16.5% and 13.7% AFR are equal. Peak temperatures are around 1480C, as are the burnout values (T_{CO_2} = 97%). When the atomizing air is reduced to 11.6% of the fuel mass flow rate the temperature drop is significant; the peak temperature reaches only 1295C. This drop in temperature is accompanied by a drop in burnout down to 94%.

A complete temperature field of a flame with a 14% atomizing air/fuel ratio is shown in figure 35. Furthermore, the boundary line between forward and reverse gas flow is indicated by the dotted line and the isolines for oxygen and carbon monoxide are also given.

While the combustion performance of CWS-E was very good when using the nominal combustion air preheat of 300C, difficulties were encountered when switching over to lower preheat levels. When the preheat level was reduced from 300C to ambient temperature, while maintaining all other input conditions (SR 1, AFR and swirl) the burnout (T_{CO_2}) decreased to 89% at 190C and further to 86% at 110C (see also figure 36A). Below 100C preheat the swirl level and the atomizing air rate had to be increased for self sustained ignition; still the burnout decreased further to 89% at 45C with 22% AFR and maximum swirl (S = 2.1). Better flames were achieved when the 194mm insert was placed in the secondary air duct. This increased the secondary air velocity for SR 1 = 1.2 from 20m/s (234 insert) to 32m/s (194 insert). The increased secondary air velocity resulted in higher burnouts and more flexibility towards atomizing air rate, swirl level and gun position.

The best results when using cold combustion air, were achieved with swirl levels of 1.6 and AFR values of 18 -25%. The maximum T_{CO_2} value was 92%. Staging of combustion air had little effect on the burnout over the SR 1 range 1.2 - 1.0. For SR 1 = 0.9 the T_{CO_2} reduced to 86% (see also figure 36B).

3.6 CWS-F

The coal used to make CWS-F originated from the same area as the coal

used for CWS-A. The analysis of both coals are very similar with a slightly higher volatile content of CWS-F (28.1%).

Initially the atomization with CWS-F appeared to be very good. Visually the flame had the same appearance as observed for CWS-D and CWS-E. The atomizing air rate consumption was also comparable, around 15%.

Figure 37A and B give the burnout T_{CO_2} and T_x respectively, as a function of the atomizing air rate. The maximum burnout level reached was 97% (T_{CO_2}). It shows that the CT-8 atomizer performed better than the CY-6 atomizer.

Radial temperature profiles at AD 8 (figure 38 left hand side) show a temperature difference of 50 - 100C between the curves for the CT-8 and CY-6 with the former giving the highest values. When using the CY-10 atomizer, flame (FL-234-9), the resulting flame was only marginally stable. The radial temperature traverse was only made up to HP 80. Further insertion of the suction pyrometer probe changed the flame shape completely (figure 38 left hand side).

Towards the end of the afternoon shift of the first day of firing with CWS-F the atomization seemed to deteriorate as indicated by more and more large agglomerates appearing in the furnace.

The next day the amount of agglomerates observed was even greater. Flames of the first day could not be repeated again. The slurry needed more atomizing air and sometimes even gas support for ignition and stability (flame FL-234-11 onwards). Figure 37C shows the burnout levels reached on the second firing day for flames without gas support. T_{CO_2} values ranged from 83% to 95% with AFR values of 16 - 24%. Comparing these data to the results of the first day, burnout levels were around 8 - 10% lower with 6 - 10% more atomizing air with a deteriorating trend with time.

Radial temperature profiles at AD 8 measured on the second day showed temperature levels in the IRZ of 1200C as opposed to 1400C on the first day (see figure 38). The profile for flame FL-234-13 could only

be measured up to HP 70 since any further radial movement of the probe into the furnace would extinguish the flame.

The reason for this change in slurry characteristics appears to be related to its being exposed to air in the storage tank. The slurry was transported to the IFRF in sealed drums. Test firing started a few hours after the slurry had been transfered to the storage tank. The odour given off by the slurry indicated that it contained an ammonium based additive. The presence of a nitrogen containing additive also was indicated by the NO_x emissions from CWS-F flames which were the highest for all the slurries (around 900 ppm NO_x (0% O_2)).

Although the lids on the road tanker were closed the additive may have slowly evaporated as the slurry filled only half the road tanker volume. Although the water content was the same and the slurry still seemed to have the same flow properties on the second day as before, the poor atomizability indicated that a change in the characteristics did take place.

3.7 CWS-G

This slurry made from a high volatile coal (33.4% d.a.f.) had the finest particle size distribution of the seven slurries; 94% passing through 75 µm and 66% < 20 µm by wet sieve technique. The solids content of the slurry (67.3%) was somewhat lower than the other CWS's.

In spite of the higher water content and the relatively low viscosity (650 cP) CWS-G needed a large amount of atomizing air to achieve self sustaining ignition. The AFR range investigated was 20 - 35% with a typical operating value of 27%. The visual flame appearance was a rather short flame with ignition well within the quarl. It appeared however that a fair amount of agglomerated particles were formed. These agglomerates were mostly of an "intermediate" size, approximately 0.5 - 1.0mm with very few particles larger than 1 mm. However, the number of intermediate sized agglomerates was large enough to have a negative effect on the final burnout.

Figure 39A shows the burnout as a function of atomizing air rate. It shows that below 27% there is a decrease in burnout. These flames were all achieved using the T-jet atomizer. Using either a standard Y-jet or divergent Y-jets, stable flames were very hard to achieve. Therefore only the T-jet was used for CWS-G. The ten-hole version gave a higher burnout than the eight-hole T-jet (figure 39A). However, flames produced with the CT-10 atomizer were very sensitive to the position of the fuel gun. Apparently the CT-10 atomizer needed to have the droplet spray exactly matched with the aerodynamic flow pattern. When moved out of the optimum position the flame would change to a asymmetric shape or even extinguish.

Swirl did not have a big effect on the combustion performance. The burnout increased slightly with increasing swirl, from 92% to 95% when increasing swirl from 0.47 to 1.44; see also figure 39B. The isotherms for these two swirl levels are shown in figure 40. Apart from a zone with high temperatures for the S = 0.47, case the temperature fields are similar. The dependence of the burnout on the primary zone stoichiometry is shown in figure 39C. The optimum SR 1 seems to be between 1.0 and 1.2.

When firing CWS-G with cold combustion air, self sustained ignition was only achieved with great difficulty. Using the CT-10 atomizer and careful positioning of the fuel gun and adjustment of the swirl level, a burnout level of 90% was reached (flame GL-234-25). Changing over to a staged flame (SR 1 = 0.8) while maintaining the secondary air velocity by using the 194mm insert raised the burnout to 92%. The flames were not very stable and no more experiments with cold air were carried out. Flames were relatively stable for combustion temperatures greater than 250C.

3.8 HEAT TRANSFER CHARACTERISTICS

The measured heat transfer for the CWS flames was not a strong function of slurry type. In figure 41 the heat flux profiles are shown for the slurries D, E, F, and G. These profiles are typical for any of the slurries fired with 300C preheat into a 3/4 furnace coverage condition.

The furnace efficiency, η_f, as defined by the heat removed by the furnace cooling water divided by the total thermal input was around 45%. The heat balance closure varied in the range 90 - 98% which indicates reasonable accuracy when taking into account that the burnout varied in the same range.

Heat flux profiles for various primary zone stoichiometries are plotted in figures 42 and 43 for FC =1/4 and FC = 0 respectively. In both cases SR 1 = 0.8 gives the highest peak values. The profiles for SR 1 = 1.0 and 1.2 are almost identical. For SR 1 = 0.6 the peak value is the lowest and the profile is much flatter when compared to the higher primary zone stoichiometries.

Heavy fuel oil was also fired into the 3/4 furnace insulation case for comparison. The heat transfer of the HFO flame was considerably higher when compared to the CWS flames.

Figure 44 shows the measured heat fluxes for HFO and one of the better, high volatile coal, slurries (CWS-E). Peak values for HFO were 91kW/m^2 at AD 50 as opposed to 68kW/m^2 at AD 90 for CWS-E. For comparison the heat flux profile of a medium volatile coal (27% d.a.f.) fired as a dry coal under the same conditions in other experimental work [9] is plotted in the same figure. Also the pulverized coal flame gives a higher heat flux than the slurry; the peak value is 80kW/m^2 at AD 60.

The effect of furnace coverage on the heat extraction rate can be seen in figure 45. Three heat flux profiles are plotted for CWS-A corresponding to the three furnace insulation conditions. As the coverage is reduced to 1/4 and 0 the peak heat flux increases to 95kW/m^2 and 140kW/m^2 respectively.

The radiative heat flux profile and emissivities (Schmid method) has been measured with the narrow angle probe. The data are plotted in figures 46, 47 and 48 for CWS-D, E and HFO respectively. The accuracy and reproducibility of the emissivity measurements were ($\pm$ 20%) affected by the uneven build-up of slag on the furnace walls which caused local variation in wall emissivities, especially near the

quarl exit.

For the slurry flames the maximum emissivity was measured to be 0.4 at AD 6. At AD 25 the emissivities reduced to 0.30 for CWS-D and 0.22 for CWS-E.

The in-flame measurements for the HFO flame can be found in figures 49 and 50. For CWS-D detailed measurements are shown in figures 29 and 30 (flame DL-234-13) and for CWS-E in figure 35 (flame EL-234-13).

The major reason for the lower heat transfer intensities of the slurry flames is perhaps due to the lower flame temperatures. As can be seen in figure 50 where the isotherms for the CWS-E and HFO flames are plotted, the peak temperatures for the slurry flame are 200C lower. But also the overall temperature field up to AD 60 is 200C lower, and as the flame radiation is a very strong function of temperature, T^4, it is to be expected that the heat flux for the HFO flame should be significantly higher.

3.9 COMPARISON OF THE SEVEN SLURRIES

This paragraph documents a comparison of the combustion performance of the seven slurries tested in terms of burnout, in-flame solid samples, atomizing air consumption, turndown, secondary air preheat, NO_x emissions and handling properties. A summary of the combustion performance of the seven slurries tested is listed in table 14.

- In-flame solid samples

  In-flame solid samples were collected for a few selected flames fired with the nominal input conditions, i.e. FC= 3/4 and T_{sec} = 300C. The samples were taken at various axial distances, from 5cm to 80cm downstream of the quarl exit plane. The radial positions were different for the various axial distances depending on the path of the coal jet.

  The data are collected in figure 51 for CWS-E and CWS-G and in figure 52 for CWS A, C and D.

In figure 51 the solids concentration C_o as well as the total combustibles burnout T_x are shown. In order to correlate the data with the burner near field aerodynamic flow patterns, the boundary line separating forward and reverse gas flow regions is indicated by means of a dotted line.

As can be seen from the solids concentration profile, the coal jets are located around the interface between forward and reverse gas flows up to an axial distance of 25cm. Also the burnout, T_x, peaks at this interface. The difference in the peak concentration values for the two slurries is probably due to the non-axisymmetric distribution of the coal as a result of a discrete number of exit holes in the atomizer.

The better atomization of CWS-E when compared to CWS-G, results in a higher combustion rate for CWS-E, in spite of the much finer initial particle size distribution of CWS-G. T_x values at AD 8 vary from 50 - 74% for CWS-E as opposed to 25 - 32% for CWS-G.

Further downstream most of the coal particles are near the furnace walls. Since there was a gradual contraction linking the furnace and the flue gas duct, the majority of the particles would remain close to the walls even after the end of the IRZ. This was especially the case for the larger particles. Solid samples which were collected for CWS-E at AD 60 for horizontal positions 100 and 110, showed the latter to contain many more large particles. At HP 110 35% by wt. of the particles were greater than 250 μm with at HP 100 only 12% > 250 μm.

For both CWS-D and CWS-E, similar combustion rates were observed (figures 51 and 52).

The burnout values at AD 15, 35 and 60 were equal for both slurries. Only at AD 8 is T_x lower for CWS-D when compared to CWS-E. Maximum T_x at AD 8 is 47% for CWS-D.

However, due to the large gradients found for T_x at this axial distance the maximum value may have been missed.

In general CWS-A gives a lower combustion rate than CWS-D or CWS-E (figure 52A). The lower volatile matter content in the coal could be a factor of importance in this case. For CWS-C, the poor atomization performance is reflected in the burnout values of the in-flame samples. A maximum of 32% was recorded at AD 35.

- Atomizing air

As already discussed in proceeding sections, the slurries showed rather different properties with regard to atomizing perfomance. An overview of the combustion efficiency as a function of the atomizing air rate is shown in figure 53. Three slurries, namely A, D and E, could be atomized successfully with an atomizing air rate of 15 - 17%. For the slurries B, C and G a much higher atomizing air rate was required for good combustion (25 - 28%). CWS-F was a special case. It belonged to the better group on the first firing day but on the second day the atomizing and combuston performance was significantly worse. In figure 53 this is indicated with a second curve labelled F'. The ease with which a slurry can be atomized and the formation of large agglomerated particles does not seem to be directly related to coal properties, but rather related to the additives.

Two of the slurries that gave a poorer combustion performance were made with high volatile coals. Furthermore the slurry with the coarsest particle size distribution, CWS-E, was very much superior to the CWS with the finest distribution (CWS-G). Also a lower coal loading in the slurry does not seem to lead directly to better atomization. CWS-E which had a 71.7% coal content gave a superior combustion performance to CWS-G which had a 67.3% coal loading.

When relating the combustion performance of the slurries, in terms of the minimum atomizing air rate required for good combustion, to the apparent viscosity at 100 s^{-1} no obvious correlation can be found (see also figure 54). However, it is possible that a correlation could be found between a slurry atomizing performance and shear rates more representative of the actual shear rate in the atomizer; probably 10^3 - 10^4 s^{-1}.

The effect of time on the viscosity as observed for two slurries is also shown in figure 54 by means of a dotted line. For CWS-F a change was seen over a one day time interval as discussed above. CWS-A, which was the baseline slurry for the burner parameter assessment, was stored in the road tanker for a total period of three weeks. During the last days of firing with this CWS, a change in handling and combustion performance was observed. The minimum atomizing air rate was a little higher; 20% instead of 17%. The viscosity was measured again and found to be 1500 cP as opposed to 780 cP in the first week. For the other slurries no change in quality was seen over the test firing periods.

- Turndown

In agreement with the relative atomization performance of the slurries the best turndown ratios were achieved with CWS-A, D and E. The maximum turndown for CWS-D was 2 : 1 with a corresponding burnout of 95% (flame DL-234-14). With CWS-A and E, a 3:1 turndown was achieved, but for the latter only when the swirl level was increased to S = 2.1 (flames AL-234-4 and EL-234-9).

Turndown for CWS-G was limited to 2 : 1 with maximum swirl level applied (flame GL-234-17). In the cases of CWS-B, C and F, turndown tests were not executed.

- Combustion air preheat temperature

Again the slurries with the best atomizing characteristics gave also the best results with reduced combustion air preheat levels. Using cold combustion air (35C) CWS-A, D and E could be fired without gas support. CWS-G was a borderline case with only a self sustained flame established with careful adjustment of swirl level and gun position.

Comparing CWS A, D and E, the slurries with the finer particle size distributions, A and D, gave more flexibility and in general better results. In the case of CWS-E the 194mm insert had to be used to increase the secondary air velocity to achieve acceptable flames. The maximum burnout was 92% for CWS-E and 96-99% for CWS A and D. CWS-B and C could not be fired without combustion air preheat. The

minimum temperature level of CWS-B was 260C. For slurry B the low volatile content (18.7%) in the coal may also have had significant influence on the need for air preheat to achieve stable ignition.

Cold combustion air firing tests were not carried out for CWS-F because of the change in characteristics of this slurry.

- NO_x

Generally NO_x emissions were similar or somewhat lower to what could be expected from the parent coal. For instance, the parent coal of CWS-B, the Beckley coal, was also fired in recent NO_x studies at the IFRF [10]. Then the NO_x level measured for a baseline flame was 570 ppm (0% O_2). CWS-B gave in this experimental work 530 ppm NO_x for the baseline flame. The NO_x data for all slurries are collected in figure 55. The NO_x emissions, corrected to 0% O_2, are plotted as a function of the primary zone stoichiometry for two swirl levels. It shows that staging of combustion air can decrease NO_x levels for some of the slurries, particularly those made with high volatile bituminous coals.

The NO_x emissions can be correlated reasonably well to the volatile fraction of the nitrogen content in the coal, N_{vol}, as can be seen in figure 56a. Also when the NO_x is plotted versus a parameter, such as volatile nitrogen content and total oxygen content, a good agreement is seen. The only exception in the two diagrams is CWS-F. This however was the slurry containing an ammonium-based additive which might explain the increased NO_x emissions.

- Handling properties

Concerning the handling aspect of the experimental work, none of the seven slurries caused any major difficulties. Hardpack formation was not observed in the storage tank. Some of the slurries would give blockages of the 1.4mm filter screen in the burner supply line faster than others. Especially CWS-B contained a significant fraction of large particles. CWS-D and G would also give filter blockages rather frequently. For these slurries, this

was not caused by large particles but appeared as gradual clogging of the screen. A relative assessment of the handling properties would yield CWS-C and CWS-E as the best followed by F, A, D and G and CWS-B as the worst.

4. CONCLUSIONS

The major factor effecting the combustion of coal water slurries is the quality of its atomization. For this, both the atomizer design and slurry characteristics are important in achieving a fine droplet size distribution in the spray. Once good atomization has been accomplished, other slurry, burner and furnace parameters such as coal particle size, coal type, combustion air temperature, etc. become important.

In this experimental work Y-jet and T-jet type atomizers proved to be capable of atomizing seven different slurries succesfully. Regarding the number of exit-holes of the atomizers, the eight-hole versions tended to give better results than the atomizers with either six or ten exit-holes. With a 35° half angle quarl, the optimum atomizer spray half angle was 25°.

The best performance over the widest range of slurry types and input conditions was given by the eight-hole T-jet atomizers.The atomizing air quantity required to give stable flames with a good final burnout varied considerably for the various slurries. For the best slurry, a 14% atomizing air to fuel ratio (w/w) was needed as opposed to 28% for the worst.

Steam atomization proved to be inferior to air atomization. The characteristics of the slurry which determine its atomizability are not clear from these experiments. There seems to be no apparent relation between the viscosity at a shear rate of 100 s^{-1} and the atomizability.

Using 300C combustion air preheat all seven slurries could be fired without gas support into the 3/4 insulated furnace. Under these input conditions burnout levels in the range of 95 - 99% were measured. The

three slurries A, D and E that could be atomized with low rates of atomizing air also could be fired without air preheat, without a significant drop in performance.

In general, once good atomization was achieved, a high volatile matter content in the coal and a finer particle size distribution gives more flexibility regarding ignition particularly when operating without air preheat or under high flame heat extraction rate conditions. The same slurries giving the most flexibility regarding ignition also gave the highest coal burnout levels.

For a circular swirl burner of a 2.5MW thermal scale, the following design criteria, apart from the atomizer, are recommended for water tube boiler conditions:

- quarl half angle: $\alpha = 35^{o}$
- quarl L/D: 1.1
- secondary air velocity: 30 - 40m/s

- SR 1: to maximize burnout: SR 1 between 1 and 1.2,
  : to lower NO_x emissions: SR 1 = 0.8,

- Swirl level: 300C air preheat: S = 0.9
  : ambient air temperature: S = 1.6

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TABLES

CNS		A	B	C	D	E	F	G
Manufacturer		I	I	II	I	III	II	IV
COAL		Virg. 26 mvb	Beckley lvb	Moss I hvb	Coal Mountain hvb	Nova Scotia hvb	McClure mvb	Corton-wood hvb
Volatiles	% daf	26.2	18.7	30.7	35.9	37.5	28.1	33.4
Ash	% db	8.1	6.2	6.7	5.8	1.46	7.9	5.7
LCV	MJ/kg db	31.6	33.3	32.5	32.8	34.2	32.9	32.2
C	% daf	86.04	89.21	86.41	86.26	85.63	88.14	84.77
H	% daf	4.97	4.62	5.25	5.36	5.50	5.17	5.31
O	% daf	6.25	3.60	5.56	5.93	6.22	3.63	6.84
S	% daf	1.12	1.06	0.87	0.96	0.79	1.05	1.36
N_{tot}	% daf	1.55	1.60	1.74	1.55	1.78	1.66	1.72
N_{fix}	% daf	1.29	1.43	1.32	1.13	1.10	1.13	1.30
N_{vol}	% daf	0.25	0.17	0.39	0.42	0.68	0.53	0.42
CWS								
Coal content	% w/w	70.4	70.4	70.0	69.6	71.7	70.4	67.3
Apparent viscosity ($100\ s^{-1}$)	cP	780	940	n.m.	1830	1420	280	630

(nm = not measured ; manufacturers specification : 1188 cP at $88\ s^{-1}$)

TABLE 2 - CWS AND COAL PROPERTIES

HFO		
C	% wt.	86.88
H	%	11.14
O	%	0.61
S	%	0.94
N	%	0.26
LCV	MJ/kg	41.20

NG		
CH_4	% vol.	85.3
C_2H_6	%	5.6
C_3H_8	%	1.2
C_nH_m	%	0.6
CO_2	%	0.1
N_2	%	7.2
LCV	MJ/kg	43.85

TABLE 3 - HFO and Natural gas composition

Flame			AL-234-1	AL-234-2	AL-234-3	AL-234-4	AL-234-5	AL-234-6	AL-234-7	AL-234-8
CMS		MW	2.39	2.35	2.35	0.78	2.28	2.28	2.28	2.24
NG		MW	-	-	-	-	-	-	-	-
SR1			0.84	1.21	1.24	1.20	1.06	0.83	0.83	1.25
λ			1.18	1.21	1.24	1.20	1.24	1.21	1.20	1.25
T_{sec}		°C	333	324	321	272	25	280	305	325
T_{tert}		°C	262	-	-	-	26	213	267	-
S			0.9	0.9	0.9	0.9	2.1	2.1	0.47	2.1
$\dot{m}_{atm}$		kg\h	87	82	56	65	72	64	64	78
P_{atm}		bar					8.0	7.0	7.0	9.0
$\dot{m}_{atm}/\dot{m}_{CMS}$		%	22	21	14	49	19	17	17	20
Atomizer			CY-6	CY-6	CY-6	CY-6	CY-6	CY-6	CY-6	CY-6
T_{flue}		°C	1098	1055	999	635	984		1077	1025
flue gas analyses	O_2	%	4.8	4.0	3.5	5.2	4.0	3.0	4.0	4.2
	CO_2	%	14.8	15.1	15.7	14.0	14.8	16.0	15.4	14.7
	CO	ppm	-	10	-	35	-	5	10	10
	NO_x	ppm	530	585	580	310	340	675	500	
	NO_x (@ O_2)	ppm	687	723	696	412	420	788	618	
	SO_2	ppm	550	600	600	450	540	580	550	610
T_{CO_2}		%	94	98	100	91	98	100	97	99
Quarl			L	L	L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234	234	234
Furnace coverage			3/4	3/4	3/4	3/4	3/4	3/4	3/4	3/4

TABLE 4 - FLAMELIST CMS-A

Flame			AL-234-9	AL-234-10	AL-234-10[a]	AL-234-11	AL-234-11[R]	AL-234-12	AL-234-13
CWS		MW	2.28	2.28	2.28	2.28	2.34	2.28	2.28
NG		MW	-	-	-	-	-	-	-
SR1			1.23	1.25	1.25	0.99	0.81	0.82	1.21
λ			1.23	1.25	1.25	1.18	1.20	1.19	1.21
T_{sec}		°C	314	306	307	449	420	438	457
T_{tert}		°C	-	-	-				-
S			0.9	0.47	0.47	0.9	0.9	0.9	0.9
$\dot{m}_{atm}$		kg\h	73	73	64	78	83	78	78
P_{atm}		bar	8.2	8.2	7.0	9.0	9.5	9.0	9.0
$\dot{m}_{atm}/\dot{m}_{CWS}$		%	19	19	17	20	21	20	20
Atomizer			CY-6	CY-6	CY-6	CDY-6	CDY-6	CDY-6	CDY-6
T_{flue}		°C			1030	762	732	812	745
flue gas analyses	O_2	%	3.2	3.2	4.1	3.6	4.3	4.7	3.4
	CO_2	%	16.0	16.0	14.8	15.1	14.3	14.0	15.0
	CO	ppm	-	-	-	32	75	200	45
	NO_x	ppm	445	580	490	360	295	380	310
	NO_x (0% O_2)	ppm	525	684	609	434	371	490	370
	SO_2	ppm	600	600	600	600	550	470	600
T_{CO_2}		%	100	100	99	96	92	90	98
Quarl			L	L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234	234
Furnace coverage			3/4	3/4	3/4	-	-	-	-

TABLE 4 - FLAMELIST CMS-A (continued)

Flame			AL-234-14	AL-234-15	AL-234-16	AL-234-17	AL-234-18	AL-234-19	AL-234-20
CWS		MW	2.28	2.32	2.32	2.28	2.24	2.28	2.28
NG		MW	-	-	-	-	-	-	-
SR1			0.83	1.01	1.23	0.79	1.04	0.84	0.85
\			1.22	1.21	1.23	1.20	1.25	1.16	1.24
T_{sec}		°C	430	457	467	363	382	463	412
T_{tert}		°C	332	339	-	267	250	291	291
S			2.1	0.47	0.47	0.9	0.9	0.9	0.9
$\dot{m}_{atm}$		kg\h	83	87	87	72	72	68	65
P_{atm}		bar	9.5	10.0	10.0	8.0	8.0	7.5	7.2
$\dot{m}_{atm}/\dot{m}_{cws}$		%	22	23	22	19	19	18	17
Atomizer			CDY-6	CY-8	CY-8	CY-8	CY-8	CY-8	CDY-8
T_{flue}		°C	679	758	798	805	781		785
flue gas analyses	O_2	%	4.0	4.6	4.1	4.0	4.5	5.3	6.0
	CO_2	%	14.8	13.7	15.1	14.5	14.1	13.0	12.6
	CO	ppm	170	30	20	215	20	100	50
	NO_x	ppm	310	400	400	215	310	395	230
	NO_x (@ O_2)	ppm	383	512	497	266	395	528	322
	SO_2	ppm	550	520	500	600	600	540	490
T_{CO_2}		%	97	90	100	94	95	81	84
Quarl			L	L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234	234
Furnace coverage			-	-	-	-	-	-	-

TABLE 4 - FLAMELIST CWS-A (continued)

Flame			AL-234-21	AL-234-22	AL-234-23	AL-234-24	AL-234-25	AL-234-26	AL-234-27
CWS		MW	2.24	2.28	2.28	2.28	2.28	2.28	2.28
NG		MW	-	-	-	-	-	-	-
SR1			0.86	0.81	0.81	0.82	1.02	1.01	1.02
\			1.26	1.22	1.21	1.24	1.23	1.23	1.23
T_{sec}		°C	417	290	307	290	307	295	311
T_{tert}		°C	285	290	307	269	307	295	241
S			1.45	0.47	0.9	2.1	0.47	0.9	2.1
$\dot{m}_{atm}$		kg\h	93	78	78	78	78	78	78
P_{atm}		bar	9.7	9.0	9.0	9.0	9.0	9.0	9.0
$\dot{m}_{atm}/\dot{m}_{cws}$		%	24	20	20	20	20	20	20
Atomizer			CDY-8	CDY-8	CDY-8	CDY-8	CDY-8	CDY-8	CDY-8
T_{flue}		°C	745	821	828	765	833	828	826
flue gas analyses	O_2	%	5.7	4.2	4.0	4.5	4.2	4.0	3.9
	CO_2	%	12.5	14.5	14.5	14.1	14.5	14.5	14.5
	CO	ppm	60	25	20	15	20	20	55
	NO_x	ppm	225	220	270	330	430	330	300
	NO_x (0% O_2)	ppm	309	275	333	420	538	408	368
	SO_2	ppm	470	600	550	570	600	600	600
T_{CO_2}		%	85	95	94	94	96	96	96
Quarl			L	L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234	234
Furnace coverage			-	1/4	1/4	1/4	1/4	1/4	1/4

TABLE 4 - FLAMELIST CNS-A (continued)

Flame		AL-234-28	AL-234-29	AL-234-30	AL-234-32	AL-234-33[a]	AL-234-33[b]	AL-234-33[c]
CWS	%w	2.28	2.24	2.28	2.28	2.27	2.28	2.24
NG	Mw	-	-	-	-	-	-	-
SR1		1.23	0.61	0.60	0.80	0.80	0.83	0.83
λ		1.23	1.23	1.20	1.21	1.23	1.27	1.27
T_{sec}	°C	328	324	287	308	339	336	353
T_{tert}	°C	-	308	288	283	234	239	252
S		2.1	2.1	0.9	2.1	0.9	0.9	0.9
$\dot{m}_{atm}$	kg\h	82	78	74	105	66	85	78
P_{atm}	bar	9.5	9.0	8.5		7.5	10	9.0
$\dot{m}_{atm}/\dot{m}_{cws}$	%	21	21	19	27	17	22	20
Atomizer		CDY-8	CDY-8	CDY-8	CDY-8	CDY-8	CDY-8	CDY-8
T_{flue}	°C	800	836	820	798	799		
flue gas analyses	O_2 %	3.8	4.9	4.8	4.2	5.0	5.3	5.2
	CO_2 %	14.7	13.7	13.8	14.5	13.9	13.6	13.7
	CO ppm	25	35	50	30	20	30	50
	NO_x ppm	300	210	160	240	260	270	245
	NO_x (@ O_2) ppm	366	274	207	30	341	361	326
	SO_2 ppm	630	550	520	500	600	580	560
T_{CO_2}	%	98	91	89	95	92	93	94
Quarl		L	L	L	L	L	L	L
Sec. air insert (cm)		234	234	234	234	234	234	234
Furnace coverage		1/4	1/4	1/4	1/4	1/4	1/4	1/4

TABLE 4 - FLAMELIST CWS-A (continued)

Flame			AL-234-34	AL-207-2*	AL-207-3	AL-207-4	AL-207-5	AL-207-6	AL-207-6^R
CMS		MW	2.28	2.15	2.28	2.32	2.17	2.17	2.17
NG		MW	-	-	-	-	-	-	-
SR1			0.82	0.54	0.48	0.67	0.50	0.91	0.90
λ			1.22	1.28	1.22	1.26	1.28	1.31	1.30
T_{sec}		°C	349	370	287	378	337	376	400
T_{tert}		°C	246		251	442	443	380	375
S			2.1	0.4	0.75	0.75	0.75	0.75	0.75
$\dot{m}_{atm}$		kg\h	78	90*	106	120	91	96	96
P_{atm}		bar	9.0						
$\dot{m}_{atm}/\dot{m}_{CMS}$		%	20	24	28	31	24	25	26
Atomizer			CDY-8	DMS 50°	CY-6 (60°)	CY-6	CY-6	CY-6	CY-6
T_{flue}		°C	800	944	1000	1036	1073	1049	
flue gas analyses	O_2	%	4.6	6.5	4.0	5.5	4.9	4.0	3.5
	CO_2	%	14.1	12.1	14.5	13.4	14.0	15.0	15.7
	CO	µm	30	-	-	-	-	-	-
	NO_x	µm	345	300	310	395	360	580	610
	NO_x (8% O_2)	ppm	442	434	383	535	470	716	732
	SO_2	ppm	580	420	860	450	450	450	490
T_{CO_2}		%	93	83	95	91	96	100	100
Quarl			L	L	L	L	L	L	L
Sec. air insert (mm)			234	207	207	207	207	207	207
Furnace coverage			1/4	3/4	3/4	3/4	3/4	3/4	3/4

*steam atomization

TABLE 4 - FLAMELIST CMS-A (continued)

Flame			AM-181-1	AL-234-I*	AM-234-1	AM-234-2	AM-234-3**	AM-234-4	AM-234-5
CWS		MW	2.17	2.17	2.35	2.49	2.28	2.32	2.17
NG		MW	-	-	-	-	-	-	-
SR1			0.70	0.66	0.81	0.76	0.64	0.65	0.65
λ			1.31	1.30	1.16	1.08	1.24	1.21	1.27
T_{sec}		°C	309	280	325	328	311	328	320
T_{tert}		°C	371	303	262	270	328	341	353
S			1.45	1.6	2.1	2.1	2.1	2.1	2.1
$\dot{m}_{atm}$		kg\h	90	86	71	46	83**	72	58
P_{atm}		bar							
$\dot{m}_{atm}/\dot{m}_{CWS}$		%	25	24	18	11	21	18	16
Atomizer			CY-6	CY-6	CY-6	CY-6	CY-6	CY-6	CY-6
T_{flue}		°C	1090	1048	988	990	1048	1069	1048
flue gas analyses	O_2	%	4.5	5.0	3.0	2.6	4.6	4.0	5.0
	CO_2	%	14.8	13.0	16.7	17.1	13.8	15.2	14.0
	CO	µm	10	-	-	-	20	10	10
	NO_x	µm	445	320	510	505	425	410	410
	NO_x (3% O_2)	ppm	566	420	595	576	544	506	538
	SO_2	µm	540	450	600	600	550	550	500
T_{CO_2}		%	100	91	100	99	92	99	96
Quarl			M	L	M	M	M	M	M
Sec. air insert (mm)			181	234/143*	234	234	234	234	234
Furnace coverage			3/4	3/4	3/4	3/4	3/4	3/4	3/4

* "gun-insert" used to increase the bluff body to 143 mm
** steam atomization

TABLE 4 - FLAMELIST CWS-A (continued)

Flame			AM-234-6	AM-234-7	AM-234-8	AM-234-9	AM-234-10	AM-234-10^R
CMS		MW	2.17	2.35	2.24	2.28	2.28	2.28
AG		MW	-	-	0.5	-	-	-
SR1			0.67	0.87	0.74	0.84	0.82	0.82
\			1.39	1.23	1.08	1.22	1.20	1.21
T_{sec}		°C	322	319	370	406	407	420
T_{tert}		°C	358	203	345	410	410	449
S			2.1	2.1	2.1	0.47	0.9	0.9
$\dot{m}_{atm}$		kg/h	58	85	71	78	70	70
P_{atm}		bar		10.0	8.2	9.0	8.0	8.0
$\Delta_{atm}/\Delta_{CMS}$		%	16	21	19	20	18	18
Atomizer			CY-6	CY-6	CDY-6	CY-8	CY-8	CY-8
T_{flue}		°C	1076	1088	823	770	799	807
flue gas analyses	O_2	%	6.2	3.7	5.2	7.6	4.3	4.2
	CO_2	%	12.8	14.7	12.0	11.1	14.4	14.8
	CO	ppm	10	-	15	50	25	20
	NO_x	ppm	410	660	280	200	310	320
	NO_x (8% O_2)	ppm	582	801	372	313	390	400
	SO_2	ppm	465	600	260	430	570	600
T_{CO_2}		%	96	97	71	73	93	97
Quarl			M	M	M	M	M	M
Sec. air insert (mm)			234	234	234	234	234	234
Furnace coverage			3/4	3/4	-	-	-	-

TABLE 4 - FLAMELIST CMS-A (continued)

Flame			AM-234-11	AM-234-11^{R}	AM-234-12	AM-234-13	AM-234-14
CWS		MW	2.32	2.28	.2.28	2.28	2.28
NG		MW	-	-	-	-	-
SRl			1.04	1.04	.1.22	0.80	0.81
\			1.23	1.24	1.22	1.19	1.22
T_{sec}		°C	410	400	418	413	365
T_{tert}		°C	380	339	-	440	378
S			0.47	0.47	0.47	0.9	0.47
$\dot{m}_{atm}$		kJ\h	72	70	70	58	70
P_{atm}		bar	8.3	8.0	8.0	6.5	8.0
$\dot{m}_{atm}/\dot{m}_{cws}$		?	18	18	18	15	18
Atomizer			CY-8	CY-8	CY-8	CY-8	CY-8
T_{flue}		°C	826	803	800	867	839
flue gas analyses	O_2	%	4.5	4.2	6.2	5.0	5.0
	CO_2	%	14.1	14.1	12.7	14.3	13.8
	CO	ppm	20	20	23	95	40
	NO_x	ppm	400	390	300	270	200
	NO_x (@ O_2)	ppm	509	488	426	354	263
	SO_2	ppm	560	600	490	560	550
T_{CO_2}		%	94	94	84	91	90
Quarl			M	M	M	M	17
Sec. air insert (mm)			234	234	234	234	234
Furnace coverage			-	-	-	-	1/4

TABLE 4 - FLAMELIST CWS-A (continued)

Flame			BL-234-1	BL-234-2	BL-234-3	BL-234-3[B]	BL-234-4*	BL-234-5*	BL-234-6*
CWS		MW	2.03	1.85	1.88	1.85	1.85	1.85	1.85
NG		MW	0.29	0.49	0.49	0.49	0.50	0.50	0.50
SR1			1.19	1.17	1.16	1.18	1.21	1.01	0.82
λ			1.19	1.17	1.16	1.18	1.21	1.21	1.21
T_{sec}		°C	314	310	310	316	313	304	299
T_{tert}		°C	-	-	-	-	-	156	200
S			0.47	2.1	0.47	0.47	0.47	0.47	0.47
$\dot{m}_{atm}$		kg\h	62	79	64	54	90*	90*	90*
P_{atm}		bar	7.0	9.2	7.2	6.0	12.8	12.8	12.8
$\dot{m}_{atm}/\dot{m}_{CWS}$		%	19	27	22	18	31	31	31
Atomizer			CDY-8	CDY-8	CDY-8	CDY-8	CDY-8	CDY-8	CDY-8
T_{flue}		°C	749	748	776	776	586	650	570
flue gas analyses	O_2	%	4.5	4.5	4.2	3.8	11.9	9.5	10.7
	CO_2	%	12.6	11.8	12.1	13.1	5.6	7.6	6.2
	CO	ppm	120	24	210	135	0.4%	0.8%	0.36%
	NO_x	ppm	190	100	210	220	100	120	130
	NO_x (0% O_2)	ppm	242	127	263	269	231	219	265
	SO_2	ppm	400	385	360	430	150	120	120
T_{CO_2}		%	83	77	80	88	30	46	34
Quarl			L	L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234	234
Furnace coverage			1/4	1/4	1/4	1/4	1/4	1/4	1/4

*steam atomization (T = 220 °C)

TABLE 5 - FLAMELIST CWS-B

Flame			BL-234-7	BL-234-8	BL-234-9	BL-234-10	BL-234-11[a]	BL-234-11[b]	BL-234-12[a]
CWS		MW	1.85	1.85	1.85	0.60	2.34	2.34	2.34
NG		MW	0.50	0.50	0.50	0.16	-	-	-
SR1			0.79	0.98	1.18	1.23	0.80	0.80	1.02
λ			1.18	1.18	1.18	1.23	1.18	1.18	1.22
T_{sec}		°C	294	296	310	277	330	330	299
T_{tert}		°C	206	213	-	-	275	275	223
S			0.47	0.47	0.47	2.1	0.9	2.1	2.1
$\dot{m}_{atm}$		kg\h	70	70	70	62	98	109	109
P_{atm}		bar	8.0	8.0	8.0	7.0	11.6	13.0	13.0
$\dot{m}_{atm}/\dot{m}_{CWS}$		%	24	24	24	66	26	29	29
Atomizer			CDY-8	CDY-8	CDY-8	CDY-8	CDY-8	CDY-8	CDY-8
T_{flue}		°C	725	696	720	445	1023	999	988
flue gas analyses	O_2	%	4.5	3.6	3.3	6.5	3.8	3.8	3.8
	CO_2	%	12.0	13.0	13.8	10.5	14.5	14.5	14.5
	CO	ppm	200	95	50	400	25	10	-
	NO_x	ppm	200	270	300	300	380	390	390
	NO_x (@ O_2)	ppm	255	326	356	434	464	476	476
	SO_2	ppm	400	380	410	290	510	510	550
T_{CO_2}		%	79	87	94	71	92	92	95
Quarl			L	L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234	234
Furnace coverage			1/4	1/4	1/4	1/4	3/4	3/4	3/4

TABLE 5 - FLAMELIST CWS-B (continued)

Flame			BL-234-12[b]	BL-234-13[a]	BL-234-13[b]	BL-234-14[a]	BL-234-14[b]	BL-234-15[a]
CWS		MW	2.34	2.34	2.34	2.37	2.37	2.37
NG		MW	-	-	-	-	-	-
SR1			1.02	1.21	1.21	0.80	0.80	0.97
λ			1.22	1.21	1.21	1.20	1.20	1.17
T_{sec}		°C	293	307	291	328	310	316
T_{tert}		°C	223	-	-	278	278	240
S			0.9	0.9	2.1	2.1	0.9	0.9
$\dot{m}_{atm}$		kg\h	109	109	109	109	84	84
P_{atm}		bar	13.0	13.0	13.0	13.0	9.8	9.8
$\dot{m}_{atm}/\dot{m}_{cws}$		%	29	29	29	29	22	22
Atomizer			CDY-8	CDY-8	CDY-8	CY-8	CY-8	CY-8
T_{flue}		°C	1001	1007	982	957	985	983
flue gas analyses	O_2	%	3.1	4.3	3.7	4.3	4.1	3.9
	CO_2	%	14.8	13.7	13.5	14.1	13.8	14.1
	CO	ppm	-	-	-	-	-	-
	NO_x	ppm	390	375	360	410	400	490
	NO_x (0% O_2)	ppm	458	472	437	516	497	602
	SO_2	ppm	500	550	560	550	550	650
T_{CO_2}		%	97	89	87	90	89	88
Quarl			L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234
Furnace coverage			3/4	3/4	3/4	3/4	3/4	3/4

TABLE 5 - FLAMELIST CWS-B (continued)

Flame			BL-234-15[b]	BL-234-15[bR]	BL-234-16[a]	BL-234-16[b]	BL-234-17	BL-234-18
CWS		MW	2.37	2.37	2.37	2.37	2.37	2.37
NG		MW	-	-	-	-	-	-
SR1			0.97	0.97	1.15	1.15	0.99	1.00
\			1.17	1.17	1.15	1.15	1.18	1.18
T_{sec}		°C	316	316	327	327	314	305
T_{tert}		°C	240	240	-	-	212	212
S			2.1	2.1	2.1	0.9	0.9	0.9
$\dot{m}_{atm}$		kg\h	85	85	93	93	97	89
P_{atm}		bar	10.0	10.0	11.0	11.0	11.5	10.5
$\dot{m}_{atm}/\dot{m}_{cws}$		%	22	22	25	25	26	24
Atomizer			CY-8	CY-8	CY-8	CY-8	CY-8	CDY-8
T_{flue}		°C	966	960	1025	1041	1037	986
flue gas analyses	O_2	%	3.3	3.6	3.0	3.7	4.6	3.7
	CO_2	%	14.6	14.2	15.1	14.6	13.5	14.5
	CO	ppm	-	-	-	-	-	-
	NO_x	ppm	480	465	425	450	445	650
	NO_x (8% O_2)	ppm	569	561	496	546	570	789
	SO_2	ppm	550	550	500	530	500	500
T_{CO_2}		%	91	89	93	90	85	92
Quarl			L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234
Furnace coverage			3/4	3/4	3/4	3/4	3/4	3/4

TABLE 5 - FLAMELIST CWS-B (continued)

Flame			HL-234-19	HL-234-20	HL-234-21
CWS		MW	2.37	2.37	2.37
NG		MW	-	-	-
SR1			0.79	0.99	1.19
\			1.18	1.19	1.19
T_{sec}		°C	310	317	319
T_{tert}		°C	257	236	-
S			0.9	0.9	0.9
$\dot{m}_{atm}$		kg\h	112	111	111
P_{atm}		bar	13.5	13.3	13.3
$\dot{m}_{atm}/\dot{m}_{cws}$		%	30	29	30
Atomizer			CDY-8	CDY-8	CDY-8
T_{flue}		°C	971	1023	1017
flue gas analyses	O_2	%	4.0	3.8	3.9
	CO_2	%	14.9	15.0	15.1
	CO	ppm	-	-	-
	NO_x	ppm	380	495	495
	NO_x (@ O_2)	ppm	469	604	608
	SO_2	ppm	500	550	550
T_{CO_2}		%	94	95	96
Quarl			L	L	L
Sec. air insert (mm)			234	234	234
Furnace coverage			3/4	3/4	3/4

TABLE 5 - FLAMELIST CWS-B (continued)

Flame			CL-207-1[a]	CL-207-1[b*]	CL-207-1[c]	CL-207-2[a]	CL-207-2[b]	CL-207-3[a]	CL-207-3[b]
CMS		MW	1.80	1.80	1.80	1.80	1.80	1.76	1.76
NG		MW	0.49	0.49	0.49	0.49	0.49	0.49	0.49
SR1			0.81	0.81	0.81	1.03	1.03	0.61	0.61
λ			1.22	1.22	1.22	1.23	1.23	1.20	1.20
T_{sec}		°C	319	319	319	344	344	310	310
T_{tert}		°C	326	326	326	193	193	273	273
S			0.75	0.40	1.8	0.75	1.8	1.8	0.75
$\dot{m}_{atm}$		kg\h	78	78	78	116	116	116	116
P_{atm}		bar	9.0	9.0	9.0	14.0	14.0	14.0	14.0
$\dot{m}_{atm}/\dot{m}_{CMS}$		%	27	27	27	40	40	40	40
Atomizer			CDY-8	CDY-8	CDY-8	CDY-8	CDY-8	CDY-8	CDY-8
T_{flue}		°C	698		691	754	729	771	766
flue gas analyses	O_2	%	6.4		7.0	7.0	6.5	8.5	8.1
	CO_2	%	10.8		10.4	10.1	10.3	9.2	8.4
	CO	ppm	55		48	30	150	160	130
	NO_x	ppm	280		280	290	260	200	190
	NO_x (0% O_2)	ppm	403		420	435	377	336	309
	SO_2	ppm	280		300	300	350	270	285
T_{CO_2}		%	74		70	68	70	59	52
Quarl			L	L	L	L	L	L	L
Sec. air insert (mm)			207	207	207	207	207	207	207
Furnace coverage			1/4	1/4	1/4	1/4	1/4	1/4	1/4

* unstable flame

TABLE 6 - FLAMELIST CMS-C

Flame			CL-234-1	CL-234-2	CL-234-3	CL-234-4	CL-234-5	CL-234-6	CL-234-7
CWS		MW	1.80	2.02	1.80	1.80	2.02	1.98	1.80
NG		MW	0.49	0.25	0.49	0.49	0.25	0.25	0.50
SR1			0.82	0.82	0.81	0.81	0.81	0.83	0.81
λ			1.24	1.22	1.21	1.20	1.21	1.24	1.21
T_{sec}		°C	335	300	306	314	314	311	311
T_{tert}		°C	236	247	247	262	262	265	265
S			0.9	0.47	0.47	0.9	0.9	2.1	2.1
$\dot{m}_{atm}$		kg\h	85	80	80	79	79	78	78
P_{atm}		bar	10.0	9.3	9.3	9.2	9.2	9.0	9.0
$\dot{m}_{atm}/\dot{m}_{CWS}$		%	29	24	27	27	24	24	27
Atomizer			CDY-8	CY-8	CY-8	CY-8	CY-8	CY-8	CY-8
T_{fluc}		°C	797	1002	1016	1045	1016	1019	1032
flue gas analyses	O_2	%	5.7	6.8	6.0	5.6	6.7	6.4	5.6
	CO_2	%	11.7	10.8	11.0	11.3	10.8	11.3	11.5
	CO	ppm	30	-	-	-	-	-	-
	NO_x	ppm	335	420	415	470	430	450	315
	NO_x (@ O_2)	ppm	459	621	581	641	631	647	430
	SO_2	ppm	320	295	285	295	320	330	490
T_{CO_2}		%	83	73	75	76	72	78	78
Quarl			L	L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234	234
Furnace coverage			1/4	3/4	3/4	3/4	3/4	3/4	3/4

TABLE 6 - FLAMELIST CWS-C (continued)

Flame		CL-234-8	CL-234-9	CL-234-10	CL-234-11	CL-234-12	CL-234-13*	CL-234-14
CWS	MW	1.80	1.98	1.98	1.80	1.80	1.98	1.80
NG	MW	0.50	0.25	0.25	0.50	0.50	0.25	0.50
SR1		1.01	1.04	1.04	1.01	1.01	1.04	1.22
λ		1.22	1.26	1.26	1.22	1.22	1.26	1.22
T_{sec}	°C	305	305	316	316	318	318	311
T_{tert}	°C	256	256	225	225	220	220	-
S		2.1	2.1	0.9	0.9	0.47	0.47	2.1
$\dot{m}_{atm}$	kg\h	79	79	79	79	80	80	79
P_{atm}	bar	9.2	9.2	9.2	9.2	9.3	9.3	9.2
$\dot{m}_{atm}/\dot{m}_{CWS}$	%	27	24	24	27	27	24	27
Atomizer		CY-8	CY-8	CY-8	CY-8	CY-8	CY-8	CY-8
T_{flue}	°C	1030	973	976	1021	1011		1028
flue gas analyses	O_2 %	5.3	6.4	6.9	6.2	6.7		4.2
	CO_2 %	11.7	11.4	10.7	10.9	10.4		12.9
	CO ppm	-	-	-	-	-		-
	NO_x ppm	500	395	400	480	470		560
	NO_x (0% O_2) ppm	669	568	596	681	690		700
	SO_2 ppm	325	345	335	305	290		340
T_{CO_2}	%	81	80	74	75	70		92
Quarl		L	L	L	L	L	L	L
Sec. air insert (mm)		234	234	234	234	234	234	234
Furnace coverage		3/4	3/4	3/4	3/4	3/4	3/4	3/4

*unstable flame

TABLE 6 - FLAMELIST CWS-C (continued)

Flame		CL-234-15	CL-234-16	CL-234-17	CL-234-18	CL-234-18[a]	CL-234-18[R]	CL-234-19
CWS	MW	1.80	1.80	2.02	2.24	2.24	2.24	2.24
NG	MW	0.50	0.50	0.25	-	-	-	-
SR1		1.22	1.22	1.23	0.86	0.85	0.85	1.25
\		1.22	1.22	1.23	1.22	1.27	1.25	1.25
T_{sec}	°C	311	311	316	348	340	296	315
T_{tert}	°C	-	-	-	282	279	199	-
S		0.47	0.9	2.1	0.9	0.9	0.9	0.9
$\dot{m}_{atm}$	kg\h	79	79	82	83	82	93	93
P_{atm}	bar	9.2	9.2	9.5	9.6	9.5	11.0	11.0
$\dot{m}_{atm}/\dot{m}_{CWS}$	%	27	27	25	23	23	25	25
Atomizer		CY-8	CY-8	CY-8	CY-8	CY-8	CY-8	CY-8
T_{flue}	°C	1048	1041	1022	1036	1050	962	1060
flue gas analyses	O_2 %	5.2	4.7	3.9	4.0	4.5	4.0	4.3
	CO_2 %	12.1	12.6	13.5	14.5	14.2	14.8	13.5
	CO ppm	-	-	-	-	-	-	-
	NO_x ppm	590	580	540	500	470	470	620
	NO_x (0% O_2) ppm	784	747	663	618	598	581	780
	SO_2 ppm	320	330	365	470	455	500	460
T_{CO_2}	%	85	89	94	96	98	100	92
Quarl		L	L	L	L	L	L	L
Sec. air insert (mm)		234	234	234	234	234	234	234
Furnace coverage		3/4	3/4	3/4	3/4	3/4	3/4	3/4

TABLE 6 - FLAMELIST CWS-C (continued)

Flame		CL-234-19[R]	CL-234-20	CL-234-21	CL-234-22[R]	CL-234-23	CL-234-23[a]	CL-234-24
CWS	MW	2.24	2.24	2.24	2.24	2.20	2.24	2.24
NG	MW	-	-	-	-	-	-	-
SR1		12.7	1.06	0.85	0.84	0.86	1.05	0.83
		1.27	1.25	1.21	1.25	1.23	1.26	1.25
T_{sec}	°C	327	317	311	315	316	330	316
T_{tert}	°C	-	160	236	259	250	250	256
S		0.9	0.9	0.9	0.9	0.9	0.9	0.9
$\dot{m}_{atm}$	kg\h	93	88	93	93	93	93	109
P_{atm}	bar	11.0	10.5	11.0	11.0	11.0	11.0	13.0
$\dot{m}_{atm}/\dot{m}_{CWS}$	%	25	24	25	25	26	25	30
Atomizer		CY-8	CY-8	CDY-8	CY-6	CY-8	CY-8	CDY-8
T_{flue}	°C	1011	940	918	964	954	970	952
flue gas analyses	O_2 %	4.5	5.3	4.5	4.2	4.0	3.5	4.9
	CO_2 %	14.5	13.1	13.6	14.5	14.8	14.8	13.8
	CO ppm	-	-	-	-	-	-	-
	NO_x ppm	580	520	460	450	480	620	460
	NO_x (@ 0% O_2) ppm	738	696	585	563	593	744	600
	SO_2 ppm	460	425	450	465	465	480	430
T_{CO_2}	%	100	89	89	98	99	100	94
Quarl		L	L	L	L	L	L	L
Sec. air insert (mm)		234	234	234	234	234	234	234
Furnace coverage		3/4	3/4	3/4	3/4	3/4	3/4	3/4

TABLE 6 - FLAMELIST CWS-C (continued)

Flame			CL-234-25	CL-234-26	CL-234-27
CWS		MW	2.24	2.24	2.24
NG		MW	-	-	-
SR1			0.81	1.25	1.06
\			1.22	1.25	1.26
T_{sec}		°C	324	337	310
T_{tert}		°C	267	-	222
S			0.9	0.9	0.9
$\dot{m}_{atm}$		kg\h	104	97	105
P_{atm}		bar	12.4	11.5	12.5
$\dot{m}_{atm}/\dot{m}_{CWS}$		%	28	27	29
Atomizer			CY-8	CY-8	CY-8
T_{flue}		°C	951	1006	994
flue gas analyses	O_2	%	4.4	5.0	4.8
	CO_2	%	14.2	13.6	14.0
	CO	ppm	-	-	-
	NO_x	ppm	515	620	630
	NO_x (8% O_2)	ppm	652	814	817
	SO_2	ppm	420	450	435
T_{CO_2}		%	94	92	96
Quarl			L	L	L
Sec. air insert (mm)			234	234	234
Furnace coverage			3/4	3/4	3/4

TABLE 6 - FLAMELIST CWS-C (continued)

Flame			DL-234-2[R]	DL-234-3	DL-234-4			DL-234-5	DL-234-6
CHS		MW	2.17	2.17	2.17			2.17	2.17
NG		MW	-	-	-			-	-
SR1			1.04	0.99	0.87	0.85	0.84	1.22	1.23
\			1.25	1.26	1.28	1.25	1.24	1.22	1.23
T_{sec}		°C	310	315	296	308	308	335	304
T_{tert}		°C							
S			2.1	0.9	0.9	0.9	0.9	0.9	2.1
$\dot{m}_{atm}$		kg\h	86	86	86	84	62	62	62
P_{atm}		bar	10.2	10.2	10.2	9.9	7.0	7.0	7.0
$\dot{m}_{atm}/\dot{m}_{CWS}$		%	25	25	25	25	18	18	18
Atomizer			CY-0	CY-0	CY-0	CY-0	CY-0	CY-0	CY-0
T_{flue}		°C	1044			1030	1023	1071	1037
flue gas analyses	O_2	%	4.1	4.4	4.7	4.7	4.1	3.9	4.3
	CO_2	%	14.7	14.5	14.3	14.2	14.7	15.4	14.9
	CO	ppm	-	-	-	-	-	-	-
	NO_x	ppm	630	610	360	380	375	675	650
	NO_x (@ O_2)	ppm	777	772	464	490	466	829	817
	SO_2	ppm	550	480	485	490	510	550	500
T_{CO_2}		%	99	99	99	96	99	100	99
Quarl			L	L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234	234
Furnace coverage			3/4	3/4	3/4	3/4	3/4	3/4	3/4

TABLE 7 - FLAMELIST CHS-0

Flame			DL-234-6	DL-234-7	DL-234-8	DL-234-9	DL-234-10	DL-234-11	
CAS		MW		2.17	2.17	2.17	2.17	2.17	2.17
MG		MW		-	-	-	-	-	
SM1				1.22	1.23	1.04	1.28	1.26	
\				1.22	1.23	1.23	1.28	1.26	
T_{sec}		°C		304	312	309	300	303	
T_{tert}		°C							
S			2.1	2.1	0.9	2.1	0.9	0.9	0.9
$\dot{m}_{atm}$		kg/h	77	62	62	62	72	54	70
p_{atm}		bar	9.0	7.0	7.0	7.0	8.3	6.0	8.0
$\dot{m}_{atm}$ / $\dot{m}_{CWA}$		%	22.5	18.0	18.0	18.0	21.0	15.8	20.5
Atomizer			CY-8	CDY-8	CDY-8	CDY-8	CY-8	CY-8	CY-8
T_{flue}		°C	1024	1034	1042	1026		1043	1049
flue gas analyses	O_2	%	3.8	3.9	3.9		4.6	4.8	4.2
	CO_2	%	15.3	15.8	15.0		13.8	13.3	13.8
	CO	ppm	-	-	-		-	-	-
	NO_x	ppm	700	620	670		610	620	660
	NO_x (@ O_2)	ppm	855	761	823		781	804	825
	SO_2	ppm	550	500	520		530	500	550
T_{CO_2}		%	100	99	99		96	90	94
Quarl			L	L	L		L	L	L
Sec. air insert (mm)			234	234	234		234	234	234
Furnace coverage			3/4	3/4	3/4		3/4	3/4	3/4

TABLE 7 - FLAMELET CAB-O (continued)

Flame			DL-234-11	DL-234-12	DL-234-13	DL-234-14	DL-234-15		DL-234-16
CWS		MW		2.17	2.17	1.08	2.17		2.17
NG		MW	-	-	-	-	-		-
SR1				1.26	1.22	1.24	1.25		1.06
				1.28	1.22	1.24	1.25		1.28
T_{sec}		°C		307	307	292	305	305	36
T_{tert}		°C	-	-	-	-	-	-	13
S			0.9	0.9	0.9	0.9	0.9	0.9	2.1
$\dot{m}_{atm}$		kg\h	62	77	68	63	62	52	66
P_{atm}		bar	7.0	9.0	7.0	7.2	8.5	7.0	7.5
$\dot{m}_{atm}/\dot{m}_{CWS}$		%	18	22.5	20.0	36	18	15	19
Atomizer			CY-8	CY-8	CY-8	CY-8	CT-8	CT-8	CY-8
T_{flue}		°C			1072	792	1044		965
flue gas analyses	O_2	%	4.4	4.3	3.8	4.6	4.2	4.0	4.0
	CO_2	%	13.6	13.6	15.2	14.2	14.5	14.8	13.6
	CO	ppm	-	-	-	30	-	-	-
	NO_x	ppm	640	615	580	460	715	710	380
	NO_x (0% O_2)	ppm	810	773	709	589	894	877	469
	SO_2	ppm	530	490	550	430	500	500	560
T_{CO_2}		%	93	94	100	95	90	100	94
Quarl			L	L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234	234
Furnace coverage			3/4	3/4	3/4	3/4	3/4	3/4	3/4

TABLE 7 - FLAMELIST CWS-O (continued)

Flame			DL-234-17	DL-234-18			DL-234-19		
CWS		MW	2.17	2.17	2.17	2.17	2.17	2.17	2.17
NG		MW	-	-	-	-	-	-	-
SR1			1.28	1.07	1.07	1.07	1.07	1.26	1.26
\			1.28	1.28	1.29	1.29	1.29	1.26	1.26
T_{sec}		°C	35	28	28	28	28	27	27
T_{tert}		°C	-	25	25	25	25	-	-
S			2.1	2.1	2.1	2.1	2.1	2.1	2.1
$\dot{m}_{atm}$		kg\h	65	55	65	65	74	65	55
P_{atm}		bar	7.4	7.5	9.0	9.0	10.5	9.0	7.5
$\dot{m}_{atm}/\dot{m}_{CWS}$		%	19	16	19	19	22	19	16
Atomizer			CY-8	CT-8	CT-8	CT-8	CT-8	CT-8	CT-8
T_{flue}		°C	945	945	945	969	963	952	931
flue gas analyses	O_2	%	4.0	5.2	4.8	4.7	4.6	4.0	4.2
	CO_2	%	13.8	13.6	13.9	14.1	14.2	14.7	14.2
	CO	µpm	-	-	-	-	-	-	-
	NO_x	µpm	365	340	360	360	360	365	350
	NO_x (0% O_2)	ppm	451	452	467	464	464	451	438
	SO_2	µpm	500	395	410	415	415	452	420
T_{CO_2}		%	95	94	97	98	99	100	97
Quarl			L	L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234	234
Furnace coverage			3/4	3/4	3/4	3/4	3/4	3/4	3/4

TABLE 7 - FLAMELIST CWS-D (continued)

Flame			DL-234-20	DL-234-21	
CHS		MW	2.25	2.25	
NG		MW	-	-	
SR1			1.29	1.3	1.29
\			1.29	1.30	1.29
T_{sec}		°C	27	25	25
T_{tert}		°C	-	-	-
S			2.1	2.1	2.1
$\dot{m}_{atm}$		kg\h	55	77	66
P_{atm}		bar	7.5	9.0	7.5
$\dot{m}_{atm}/\dot{m}_{CHS}$		%	16	22.5	19
Atomizer			CT-6	CDY-6	CDY-6
T_{flue}		°C	931	990	988
flue gas analyses	O_2	%	4.2	4.9	5.0
	CO_2	%	14.2	13.7	13.2
	CO	ppm	-	-	-
	NO_x	ppm	350	330	320
	NO_x (0% O_2)	ppm	430	430	420
	SO_2	ppm	420	370	370
T_{CO_2}		%	99	96	92
Quarl			L	L	L
Sec. air insert (mm)			234	234	234
Furnace coverage			3/4	3/4	3/4

TABLE 7 - FLAMELIST CHS-D (continued)

Flame			EL-234-1[R]		EL-234-2	EL-234-3	EL-234-4	EL-234-5	EL-234-6
CWS		MW	2.29		2.29	2.29	2.29	2.29	2.29
NG		MW	-		-	-	-	-	-
SR1			0.99		0.99	1.18	1.19	1.17	1.18
λ			1.17		1.18	1.18	1.19	1.17	1.18
T_{sec}		°C	316	316	317	321	314	319	333
T_{tert}		°C	225	225	223	-	-	-	-
S			0.9	0.9	2.1	2.1	0.9	0.9	0.9
$\dot{m}_{atm}$		kg\h	62	46	46	47	47	39	46
P_{atm}		bar	7.2	5.0	5.0	5.0	5.0	5.0	6.0
$\dot{m}_{atm}/\dot{m}_{cws}$		%	18.5	13.7	13.7	13.7	13.7	11.5	13.7
Atomizer			CY-8	CY-8	CY-8	CY-8	CY-8	CT-8	CT-8
T_{flue}		°C	1065		1040	1044	1063	1062	1047
flue gas analyses	O_2	%	3.5	3.7	3.3	3.3	3.5	3.8	3.5
	CO_2	%	15.5	15.3	15.2	15.4	15.4	14.7	15.2
	CO	ppm	-	-	-	-	-	-	-
	NO_x	ppm	660	705	700	690	705	700	715
	NO_x (0% O_2)	ppm	792	856	831	819	846	855	858
	SO_2	ppm	445	430	450	455	465	430	420
T_{CO_2}		%	99	97	97	98	99	94	97
Quarl			L	L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234	234
Furnace coverage			3/4	3/4	3/4	3/4	3/4	3/4	3/4

TABLE 8 - FLAMELIST CWS-E

Flame			EL-234-7	EL-234-8	EL-234-9*	EL-234-10			
CWS		MW	2.29	2.29	0.78	2.29			
NG		MW	-	-	-	-			
SR1			1.18	1.17	1.19	1.18			
\			1.18	1.17	1.19	1.18			
T_{sec}		°C	320	323	282	328			
T_{tert}		°C	-	-	-	-			
S			0.9	2.1	2.1	0.9			
$\dot{m}_{atm}$		kg\h	55	46	36	50	46	39	42
P_{atm}		bar	7.5	6.0	4.7	5.5	5.0	4.0	4.5
$\dot{m}_{atm}/\dot{m}_{CWS}$		a	16.4	13.7	32.5	14.9	13.7	11.6	12.5
Atomizer			CT-8	CT-8	CT-8	CDY-8	CDY-8	CDY-8	CDY-8
T_{flue}		°C	1047	1019	668	-	1058	1069	1072
flue gas analyses	O_2	%	3.5	3.5		3.2	3.3	3.8	3.5
	CO_2	%	15.2	15.1		15.3	15.2	14.7	15.0
	CO	ppm	-	-		-	-	-	-
	NO_x	ppm	715	710		740	750	690	710
	NO_x @ 0% O_2	ppm	858	852		873	890	819	852
	SO_2	ppm	420	430		450	445	430	440
T_{CO_2}		%	97	96		98	97	94	96
Quarl			L	L		L	L	L	L
Sec. air insert (mm)			234	234		234	234	234	234
Furnace coverage			3/4	3/4		3/4	3/4	3/4	3/4

*Turndown flame (1:3); no flue gas analysis was taken because of air inleakage in the furnace.
Flue solid burnout = 98%

TABLE 8 - FLAMELIST CWS-E (continued)

Flame			EL-234-11	EL-234-12	EL-234-13	EL-234-14	EL-234-15	EL-234-16A*
CWS		MW	2.29	2.29	2.29	2.29	2.29	2.29
NG		MW	-	-	-	-	-	-
SR1			1.18	1.18	1.17	1.19	1.19	1.15
λ			1.18	1.18	1.17	1.19	1.19	1.15
T_{sec}		°C	308	312	314	309	302	303
T_{tert}		°C	-	-	-	-	-	-
S			0.9	0.9	0.9	0.9	0.9	2.1
$\dot{m}_{atm}$		kg\h	46	54	46	55	65	58
P_{atm}		bar	5	6	6	7.5	9.0	12.8
$\dot{m}_{atm}/\dot{m}_{cws}$		%	14	16	14	16	19	18
Atomizer			CDY-8	CDY-10	CT-8	CT-8	CT-8	CT-8
T_{flue}		°C		1049	1052	1056	1050	994
flue gas analyses	O_2	%	4.0	3.5	3.4	3.7	3.7	4.6
	CO_2	%	14.8	14.8	15.2	14.5	14.5	13.4
	CO	µm	-	-	-	-	-	-
	NO_x	ppm	690	680	710	670	680	500
	NO_x (0% O_2)	ppm	852	816	847	813	825	640
	SO_2	ppm	390	430	465	435	435	395
T_{CO_2}		%	95	95	97	93	94	83
Quarl			L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234
Furnace coverage			3/4	3/4	3/4	3/4	3/4	3/4

*Steam atomization, steam temperature EL-234-16A = 200 °C

TABLE 8 - FLAMELIST CWS-E (continued)

Flame			EL-234-16B*	EL-234-17	EL-234-18	EL-194-1	EL-194-2^{L}**	EL-194-2^{S}**
CMS		MW	2.29	2.29	2.29	2.29	2.29	2.29
NG		MW	-	-	-	-	-	-
SR1			1.16	1.01	1.20	0.88	1.03	1.03
\			1.16	1.22	1.20	1.17	1.24	1.24
T_{sec}		°C	303	45	45	40	39	39
T_{tert}		°C	-	46	-	37	33	33
S			2.1	2.1	2.1	1.6	1.6	1.6
$\dot{m}_{atm}$		kg\h	58	74	71	60	78	78
P_{atm}		bar	12.8	9	9	7.5	9.0	9.0
$\dot{m}_{atm}/\dot{m}_{CMS}$		%	18	22	22	18	25	25
Atomizer			CT-8	CDY-8	CDY-8	CDY-8	CDY-8	CDY-8
T_{flue}		°C	1006	969	953	994	999	999
flue gas analyses	O_2	%	4.4	5.4	5.0	4.5	4.9	4.3
	CO_2	%	13.5	12.4	12.8	13.5	13.2	13.7
	CO	ppm	-	-	-	-	-	
	NO_x	ppm	540	330	320	390	365	410
	NO_x (3% O_2)	ppm	683	444	420	496	476	516
	SO_2	ppm	390	390	400	390	385	405
T_{CO_2}		%	85	82	83	86	89	92
Quarl			L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234
Furnace coverage			3/4	3/4	3/4	3/4	3/4	3/4

* Steam atomization, steam temperature EL-234-16B = 235 °C

** Flame EL-234-2^{L} was a long flame, visible flame length ~ 1.2 m.
This long flame changed into a short flame (wall jet type); flame length < 0.25 m.

TABLE 8 - FLAMELIST CMS-E (continued)

Flame			EL-194-3	EL-194-4	EL-194-5		EL-194-6	EL-194-7	EL-234-19
CWS		MW	2.29	2.29	2.29		2.29	2.29	2.29
NG		MW	-	-	-		-	-	-
SR1			1.01	1.20	1.21	1.21	1.00	1.20	1.20
\			1.29	1.20	1.21	1.21	1.21	1.20	1.20
T_{sec}		°C	39	38	37	37	33	32	309
T_{tert}		°C	33	-	-	-	33	-	-
S			1.6	1.6	1.6	1.6	1.6	1.6	0.9
$\dot{m}_{atm}$		kg\h	63	77	85	77	60	62	66
P_{atm}		bar	7.2	8.9	10	9	7.0	7.0	7.5
$\dot{m}_{atm}/\dot{m}_{CWS}$		%	18	23	25	23	18	18	20
Atomizer			CDY-10	CDY-10	CDY-10	CDY-10	CDY-8	CDY-8	CDY-10
T_{flue}		°C		988	1000	1000	1016	1003	994
flue gas analyses	O_2	%	4.3	4.0	4.0	4.5	3.7	3.4	3.5
	CO_2	%	13.7	14.0	14.0	13.6	14.3	14.6	15.4
	CO	ppm							
	NO_x	ppm	350	340	335	330	370	400	720
	NO_x (0% O_2)	ppm	440	420	414	420	449	477	864
	SO_2	ppm	405	420	450	435	420	430	415
T_{CO_2}		%	91	91	92	90	94	95	100
Quarl			L	L	L	L	L	L	L
Sec. air insert (mm)			194	194	194	194	194	194	194
Furnace coverage			3/4	3/4	3/4	3/4	3/4	3/4	3/4

TABLE 8 - FLAMELIST CNS-E (continued)

Flame		EL-234-19		EL-234-20	EL-234-21	EL-234-22	EL-234-23	EL-234-24
CWS	MW	2.29	2.29	2.29	2.29	2.29	2.29	2.29
NG	MW	-	-	-	-	-	-	-
SR1		1.20	1.20	1.13	1.08	1.18	1.18	1.14
λ		1.20	1.20	1.13	1.08	1.18	1.18	1.14
T_{sec}	°C	309	309	292	294	307	300	300
T_{tert}	°C							
S		0.9	0.9	2.1	2.1	0.9	0.9	0.9
$\dot{m}_{atm}$	kg\h	54	46	49	46	46	39	34.5
P_{atm}	bar	6.0	5.0	5.3	5.0	5.0	4.0	3.5
$\dot{m}_{atm}/\dot{m}_{CWS}$	%	16	14	14.6	14	13.5	12.0	10.0
Atomizer		CDY-10	CDY-10	CDY-10	CDY-10	CDY-10	CDY-10	CDY-10
T_{flue}	°C	1005	1020	1036	970	991	998	
flue gas analyses	O_2 %	3.6	3.8	3.0	2.1	3.3	3.5	5.2
	CO_2 %	15.3	15.2	15.4	16.6	15.3	14.6	13.8
	CO ppm							
	NO_x ppm	690	600	450	520	510	660	500
	NO_x (0% O_2) ppm	833	733	525	578	605	792	665
	SO_2 ppm	410	430	465	475	435	430	390
T_{CO_2}	%	99	99	95	97	98	93	85
Quarl		L	L	L	L	L	L	L
Sec. air insert (mm)		234	234	234	234	234	234	234
Furnace coverage		3/4	3/4	3/4	3/4	3/4	3/4	3/4

TABLE 8 - FLAMELIST CWS-E (continued)

Flame			EL-234-25	EL-234-26	EL-234-27	EL-234-28	EL-234-29
CWS		MW	2.29	2.29	2.29	2.29	2.29
NG		MW	-	-	-	-	-
SR1			1.21	1.18	1.18	1.18	1.17
\			1.21	1.18	1.18	1.18	1.17
T_{sec}		°C	206	192	109	109	106
T_{tert}		°C					
S			0.9	0.9	0.9	0.9	2.1
$\dot{m}_{atm}$		kg\h	46	46	46	46	46
P_{atm}		bar	5.0	5.0	5.0	5.0	5.0
$\dot{m}_{atm}/\dot{m}_{cws}$		%	14	14	14	14	14
Atomizer			CDY-10	CDY-10	CDY-10	CDY-10	CDY-10
T_{flue}		°C		1022	1003	969	1003
flue gas analyses	O_2	%	3.4	3.8	4.5	4.4	3.6
	CO_2	%	14.5	13.9	13.4	13.4	14.3
	CO	ppm					
	NO_x	ppm	580	580	470	420	450
	NO_x (0% O_2)	ppm	692	708	598	531	543
	SO_2	ppm	430	410	390	380	415
T_{CO_2}		%	95	89	86	86	91
Quarl			L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234
Furnace coverage			3/4	3/4	3/4	3/4	3/4

TABLE 8 - FLAMELIST CNS-E (continued)

Flame			FL-234-1	FL-234-2		FL-234-3	FL-234-4		FL-234-5
CWS		MW	2.25	2.25		2.25	2.25		2.25
NG		MW	-	-		-	-		-
SR1			1.01	1.00	1.00	1.00	1.20	1.20	1.20
			1.22	1.21	1.21	1.21	1.20	1.20	1.20
T_{sec}		°C	312	312	312	311	319	319	292
T_{tert}		°C	243	247	247	248	-	-	-
λ			0.9	0.9	0.9	2.1	0.9	0.9	2.1
$\dot{m}_{atm}$		kg\h	65	56	46	46	56	49	49
P_{atm}		bar	9.0	7.5	6.0	6.0	7.5	6.5	6.5
$\dot{m}_{atm}/\dot{m}_{CWS}$		-	19	16	13	13	16	14	14
Atomizer			CT-8	CT-8	CT-8	CT-8	CT-8	CT-8	CT-8
T_{flue}		°C	1037	1053	1045	1030	1053		1037
flue gas analyses	O_2	%	3.9	3.7	4.2	4.3	3.6	3.7	3.5
	CO_2	%	14.8	15.0	14.2	14.2	14.9	14.9	15.0
	CO	ppm	-	-	-	-	-	-	-
	NO_x	ppm	720	720	680	710	780	750	705
	NO_x (0% O_2)	ppm	884	874	850	893	941	918	846
	SO_2	ppm	600	600	550	600	600	600	550
T_{CO_2}		%	97	97	92	92	96	96	96
Quarl			L	L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234	234
Furnace coverage			3/4	3/4	3/4	3/4	3/4	3/4	3/4

TABLE 9 - FLAMELIST CWS-F

Flame			FL-234-6	FL-234-7		FL-234-8	FL-234-9	FL-234-10	FL-234-11
CWS		MW	2.25	2.25		2.25	2.25	2.25	2.25
NG		MW	-	-		-	-	-	0.1
SR1			1.22	1.21	1.21	1.21	1.20	1.24	0.96
λ			1.22	1.21	1.21	1.21	1.20	1.24	1.16
T_{sec}		°C	302	316	316	306	299	312	309
T_{tert}		°C	-	-	-	-	-	-	283
S			2.1	0.9	0.9	0.9	0.9	0.9	0.9
$\dot{m}_{atm}$		kg/h	66	66	46	51	54	66	65
P_{atm}		bar	7.5	7.5	5.0	5.5	6.0	7.5	9.0
$\dot{m}_{atm}/\dot{m}_{CWS}$		%	19	19	13	15	15.5	19	19
Atomizer			CY-6	CY-6	CY-6	CY-6	CY-10	CY-8	CY-8
T_{flue}		°C	1035	1035		1057		1072	1066
flue gas analyses	O_2	%	3.7	3.7	4.9	3.6	3.9	3.7	4.0
	CO_2	%	14.9	14.7	13.3	14.5	14.9	14.5	14.0
	CO	ppm	-	-	-	-	-	-	-
	NO_x	ppm	690	690	610	680	700	720	630
	NO_x (0% O_2)	ppm	838	838	796	821	860	874	778
	SO_2	ppm	600	590	550	570	550	570	600
T_{CO_2}		%	97	96	86	94	96	96	87
Quarl			L	L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234	234
Furnace coverage			3/4	3/4	3/4	3/4	3/4	3/4	3/4

TABLE 9 - FLAMELIST CWS-F (continued)

Flame			FL-234-11			FL-234-12			FL-234-13
CWS		MW	2.25			2.25			2.25
NG		MW	0.1	0.05	-	0.1	0.1	0.05	-
SR1			0.96	0.98	1.00	1.14	1.14	1.16	1.20
\			1.16	1.19	1.21	1.14	1.14	1.16	1.20
T_{sec}		°C	309	309	309	300	300	300	300
T_{tert}		°C	203	203	203	-	-	-	-
S			0.9	0.9	0.9	0.9	0.9	0.9	0.9
$\dot{m}_{atm}$		kg\h	56	65	65	65	56	56	65
P_{atm}		bar	7.5	9.0	9.0	9.0	7.5	7.5	9.0
$\dot{m}_{atm}/\dot{m}_{CWS}$		%	16	19	19	19	16	16	19
Atomizer			CT-0	CT-0	CT-0	CT-0	CT-0	CT-0	CT-0
T_{flue}		°C	1066			1090	1090	1087	
flue gas analysis	O_2	%	4.2	4.3	5.0	3.9	4.4	4.7	4.6
	CO_2	%	13.8	13.9	13.7	14.0	13.7	13.4	14.0
	CO	ppm	-	-	-	-	-	-	-
	NO_x	ppm	600	535	570	575	600	585	535
	NO_x (0% O_2)	ppm	750	673	710	706	750	651	685
	SO_2	ppm	500	550	550	600	560	550	
T_{CO_2}		%	86	88	88	86	85	83.5	90
Quarl			L	L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234	234
Furnace coverage			3/4	3/4	3/4	3/4	3/4	3/4	3/4

TABLE 9 - FLAMELIST CWS-F (continued)

Flame			FL-234-14			FL-234-15	FL-234-16
CMS		Nm	2.25			2.25	2.25
NG		Nm	-			-	-
SR1			1.20	1.20	1.20	1.22	1.28
\			1.20	1.20	1.20	1.22	1.28
T_{sec}		°C	305	305	305	303	315
T_{tert}		°C	-	-	-	-	-
S			0.9	0.9	0.9	0.9	0.55
$\dot{n}_{atm}$		kg\h	77	73	85	85	85
P_{atm}		bar	9.0	8.5	10.0	10.0	10.0
$\dot{n}_{atm}/\dot{n}_{CMS}$		%	22	21	24	24	24
Atomizer			CDY-6	CDY-6	CDY-6	CDY-6	CDY-6
T_{flue}		°C	1050	1047		1043	1026
flue gas analyses	O_2	%	4.4	4.2	3.8	4.5	6.2
	CO_2	%	14.2	14.0	14.8	14.0	12.2
	CO	µgm					
	NO_x	µgm	530	500	560	540	505
	NO_x (0% O_2)	ppm	670	625	684	687	717
	SO_2	ppm					
T_{CO_2}		%	90	90	95	91	83
Quarl			L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234
Furnace coverage			3/4	3/4	3/4	3/4	3/4

TABLE 9 - FLAMELIST CMS-F (continued)

Flame			GL-234-1	GL-234-2	GL-234-3	GL-234-4	GL-234-5	GL-234-6		GL-234-7
CWS		MW	2.02	2.18	2.23	2.12	2.19	2.12		2.16
NG		MW	-	-	-	-	-	-		-
SR1			0.93	1.21	1.18	1.22	1.20	1.02	1.02	1.00
			1.38	1.21	1.18	1.22	1.20	1.24	1.24	1.11
T_{sec}		°C	305	320	322	321	280	308	3.08	308
T_{tert}		°C	282	-	-	-	-	241	2.41	249
S			0.47	0.47	0.47	0.47	0.47	0.66	0.66	2.1
$\dot{m}_{atm}$		kg\h	74	114	88	95	93	98	87	99
P_{atm}		bar								
$\dot{m}_{atm}/\dot{m}_{CWS}$		%	20	30	23	26	25	27	24	27
Atomizer			CT-8	CDY-8	CT-8	CT-8	CT-8	CT-8	CT-8	CT-8
T_{flue}		°C		967	979	960	1041	1032	1038	1053
flue gas analyses	O_2	%	6.0	3.5	3.5	3.7	3.6	4.0	4.0	3.3
	CO_2	%	12.8	14.8	14.6	14.7	14.5	14.5	14.4	14.6
	CO	ppm	-	-	-	-	-	-	-	-
	NO_x	ppm	400	655	660	590	580	600	600	670
	NO_x (8% O_2)	ppm	560	762	792	716	700	741	741	795
	SO_2	ppm				770	780	750	750	800
T_{CO_2}		%	96	97	93	97	94	96	95	96
Quarl			L	L	L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234	234	234
Furnace coverage			3/4	3/4	3/4	3/4	3/4	3/4	3/4	3/4

TABLE 10 - FLAMELIST CWS-G

Flame			GL-234-8	GL-234-9	GL-234-10	GL-234-11	GL-234-12	GL-234-13	GL-234-14
CWS		MW	2.19	2.16	2.12	2.16	2.19	2.12	2.16
NG		MW	-	-	-	-	-	-	-
SR1			0.79	0.83	1.22	1.20	1.19	1.27	1.20
λ			1.18	1.23	1.22	1.20	1.19	1.27	1.20
T_{sec}		°C	300	298	314	320	324	317	298
T_{tert}		°C	293	295	-	-	-	-	-
S			2.1	0.9	0.9	0.47	1.44	1.44	1.44
$\dot{m}_{atm}$		kg\h	99	99	101	100	99	102	80
P_{atm}		bar							
$\dot{m}_{atm}/\dot{m}_{CWS}$		%	27	27	27	27	27	27	22
Atomizer			CT-8	CT-8	CT-8	CT-8	CT-8	CT-8	CT-8
T_{flue}		°C	984	1008	1057	1076	1061	1021	1032
flue gas analyses	O_2	%	3.5	4.4	4.0	4.0	3.6	4.3	4.4
	CO_2	%	14.8	14.0	14.0	14.0	14.8	13.9	13.6
	CO	ppm	-	-	-	-	-	-	-
	NO_x	ppm	550	500	650	640	680	675	590
	NO_x (0% O_2)	ppm	660	632	803	791	821	849	746
	SO_2	ppm	800	750	750	750			
T_{CO_2}		%	94	93	93	91	95	95	88
Quarl			L	L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234	234
Furnace coverage			3/4	3/4	3/4	3/4	3/4	3/4	3/4

TABLE 10 - FLAMELIST CWS-G (continued)

Flame			GL-234-15	GL-234-16	GL-234-17	GL-234-18	GL-234-19	GL-234-20	GL-234-21
CNS		Nm	2.19	2.12	1.11	2.12	2.16	2.12	2.17
NG		Nm	-	-	-	-	-	-	-
SRI			1.20	1.22	1.21	1.24	1.23	1.23	1.24
λ			1.20	1.22	1.21	1.24	1.23	1.23	1.24
T_{sec}		°C	296	294	248	302	308	300	299
T_{tert}		°C	-	-	-	-	-	-	-
S			1.44	1.44	2.1	2.1	2.1	1.44	0.9
$\dot{m}_{atm}$		kg\h	100	129	122	120	90	90	92
P_{atm}		bar							
$\dot{m}_{atm}/\dot{m}_{CNS}$		%	27	35	63	32	24	2.4	25
Atomizer			CT-8	CT-8	CT-8	CT-10	CT-10	CT-10	CT-10
T_{flue}		°C		1032	799	1019	1045	1056	1036
flue gas analyses	O_2	%	3.5	3.8	3.5	3.6	3.7	3.7	4.2
	CO_2	%	14.8	14.4	14.8	14.8	14.5	14.4	14.1
	CO	ppm	-	-	-	-	-	-	-
	NO_x	ppm	710	710	370	780	715	680	645
	NO_x (@ O_2)	ppm	852	867	444	941	868	825	806
	SO_2	ppm							
T_{CO_2}		%	96	95	96	98	96	96	92
Quarl			L	L	L	L	L	L	L
Sec. air insert (mm)			234	234	234	234	234	234	234
Furnace coverage			3/4	3/4	3/4	3/4	3/4	3/4	3/4

TABLE 10 - FLAMELIST CNS-G (continued)

Flame			GL-234-22	GL-234-25	GL-194-1	GL-194-2	GL-194-3	GL-194-4*	GL-194-5**
CWS		MW	2.19	2.12	2.19	2.16	2.12	2.10	2.12
NG		MW	-	-	-	-	-	-	-
SR1			1.20	1.23	0.84	0.81	0.83	0.81	0.76
\			1.20	1.23	1.26	1.21	1.23	1.21	1.16
T_{sec}		°C	308	38	31	280	294	307	308
T_{tert}		°C	-	-	26	290	299	294	300
S			1.44	0.47	0.7	1.6	1.6	0.7	0.7
$\dot{m}_{atm}$		kg\h	97	84	82	96	104	76*	105**
P_{atm}		bar							
$\dot{m}_{atm}/\dot{m}_{CWS}$		%	26	23	22	26	28	21	29
Atomizer			CT-8	CT-10	CT-10	CT-10	CT-10	CT-10	CT-10
T_{flue}		°C	1046				1009	978	1031
flue gas analyses	O_2	%	4.0	4.9	4.9	5.1	4.4	5.3	4.3
	CO_2	%	14.0	13.5	13.5	13.5	13.8	13.1	14.0
	CO	ppm	-	-	-	-	-	-	-
	NO_x	ppm	580	410	300	500	540	561	430
	NO_x (0% O_2)	ppm	716	543	391	660	683	420	540
	SO_2	ppm	550	600	700	700	770		
T_{CO_2}		%	90	90	92	88	92	86	88
Quarl			L	L	L	L	L	L	L
Sec. air insert (mm)			234	234	194	194	194	194	194
Furnace coverage			3/4	3/4	3/4	3/4	3/4	3/4	3/4

* atomizing air temperature 185 °C
** steam atomization, T_{steam} = 287 °C

TABLE 10 - FLAMELIST CWS-G (continued)

Flame			NL-234-1	NL-207-1	OL-234-3
HFO		MW	-	-	2.25
NG		MW	2.2	2.0	-
SR1			1.20	1.30	1.21
\			1.20	1.30	1.21
T_{sec}		°C	315	366	311
T_{tert}		°C	-	-	-
S			0.47	1.2	0.47
$\dot{m}_{atm}$		kg\h	-	-	20
P_{atm}		bar	-	-	2.5
$\dot{m}_{atm}/\dot{m}_{CWS}$		%	-	-	10
Atomizer			-	-	IM 15/60
T_{flue}		°C	787	954	1030
flue gas analyses	O_2	%	4.1	5.0	3.9
	CO_2	%	8.7	9.0	12.3
	CO	ppm	-	-	-
	NO_x	ppm	200	125	370
	NO_x (@ O_2)	ppm	249	164	454
	SO_2	ppm	-	-	350
T_{CO_2}		%	100	100	100
Quarl			L	L	L
Sec. air insert (mm)			234	207	234
Furnace coverage			1/4	3/4	3/4

TABLE 11 - FLAMELIST NATURAL GAS AND OIL

FLAME	T_x %	FLAME	T_x %	FLAME	T_x %
AL-234- 1	93.4	AL-234-24	89.9	BL-234-20	97.2
AL-234- 2	93.5	AL-234-25	92.5	BL-234-21	97.7
AL-234- 3	87.5	AL-234-26	95.1	CL-207- 1a	75.9
AL-234- 4	82.3	AL-234-27	96.1	CL-207- 3a	74.0
AL-234- 5	86.9	AL-234-29	89.2	CL-207- 3b	75.1
AL-234- 7	93.4	AL-234-30	89.1	CL-234- 1	86.9
AL-234- 8	88.7	AL-234-32	89.2	CL-234- 3	83.0
AL-234- 9	89.1	AL-234-33a	91.2	CL-234- 4	80.4
AL-234-10	91.1	AL-234-33b	91.0	CL-234-14	91.7
AL-234-11	93.0	AM-234- 1	87.7	CL-234-17	89.4
AL-234-11R	89.8	AM-234- 2	89.4	CL-234-18	94.7
AL-234-12	91.9	AM-234- 5	87.8	CL-234-25	95.1
AL-234-14	82.2	BL-234- 1	82.5	CL-234-27	98.1
AL-234-15	85.5	BL-234- 2	81.4	DL-234- 2R	98.2
AL-234-16	83.5	BL-234- 3B	72.6	DL-234- 5	94.1
AL-234-17	90.0	BL-234-11a	85.6	DL-234- 5	95.1
AL-234-18	92.9	BL-234-11b	84.4	DL-234- 8	94.6
AL-234-20	86.9	BL-234-12a	96.3	DL-234- 8	98.7
AL-234-21	87.1	BL-234-12b	94.6	DL-234-12	97.3
AL-234-22	92.0	BL-234-14a	91.2	DL-234-13	97.9
AL-234-23	89.9	BL-234.14b	90.6	DL-234-15/2	99.0

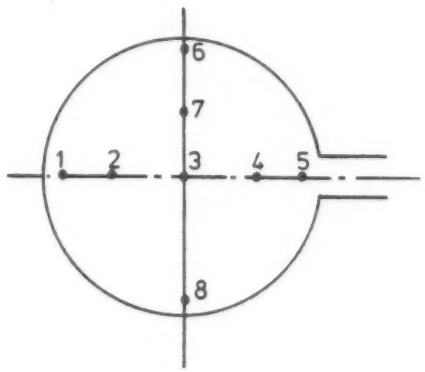
TABLE 12: Total combustible burnout of flue gas solid samples

FLAME	T_x %	FLAME	T_x %	FLAME	T_x %
DL-234-16	97.1	FL-234- 1	93.4	GL-234-12	93.4
DL-234-17	97.6	FL-234- 2	92.3	GL-234-17	96.3
EL-234- 1R	98.5	FL-234- 2	92.1	GL-234-18	96.6
EL-234- 3	96.6	FL-234- 4	95.3	GL-234-19	96.6
EL-234- 4	94.1	FL-234- 4	93.5	GL-234-21	87.2
EL-234- 5	94.2	FL-234- 5	91.8	GL-234-22	89.8
EL-234- 6	98.0	FL-234- 6	93.3	GL-194- 1	86.0
EL-234- 7	97.2	FL-234- 7	92.0	GL-194- 4	84.5
EL-234- 8	98.1	FL-234- 8	87.5	GL-194- 5	87.3
EL-234- 9	98.4	FL-234- 9	92.4		
EL-234-10	97.2	FL-234-10	91.8		
EL-234-11	92.0	FL-234-11	77.6		
EL-234-12	94.0	FL-234-11/4	90.4		
EL-234-15	88.2	FL-234-15	79.4		
EL-194- 2L	87.9	GL-234- 5	92.9		
EL-194- 3	87.4	GL-234- 6	93.9		
EL-194- 7	92.9	GL-234- 6	92.7		
EL-234-19	97.0	GL-234- 7	96.4		
EL-234-19	95.1	GL-234- 8	93.4		
EL-234-19	94.8	GL-234- 9	91.0		
EL-234-26	91.6	GL-234-10	93.9		
EL-234-27	83.6	GL-234-11	92.3		

TABLE 12: Total combustible burnout of flue gas solid samples (continued)

FLAME	SAMPLE POS.	C_o g/m^3	T_x %
AL-234-32 (S = 2.1)	1	20.9	89.4
	2	14.0	86.4
	3	9.2	89.2
	4	10.8	88.0
AL-234-33a (S = 0.9)	1	25.3	88.6
	2	17.8	89.4
	3	14.2	91.2
	4	14.3	90.1
	6	14.5	91.9
	7	11.9	91.8
	8	30.7	88.3
AM-234-14 (S = 0.47)	1	14.5	88.7
	2		85.2
	3	18.1	90.4
	4	19.2	88.1

FLAME	SAMPLE POS.	C_o g/m^3	T_x %
EL-234-13 (S = 0.9)	2	3.4	92.1
	3	2.3	98.3
	4	2.2	97.9
	5	4.2	89.9
	6	7.3	87.9
	8	5.9	85.3
GL-234-22 (S = 1.44)	2	7.3	88.8
	3	8.5	81.5
	5	8.4	96.6



Cross section of flue gas duct solid sample positions

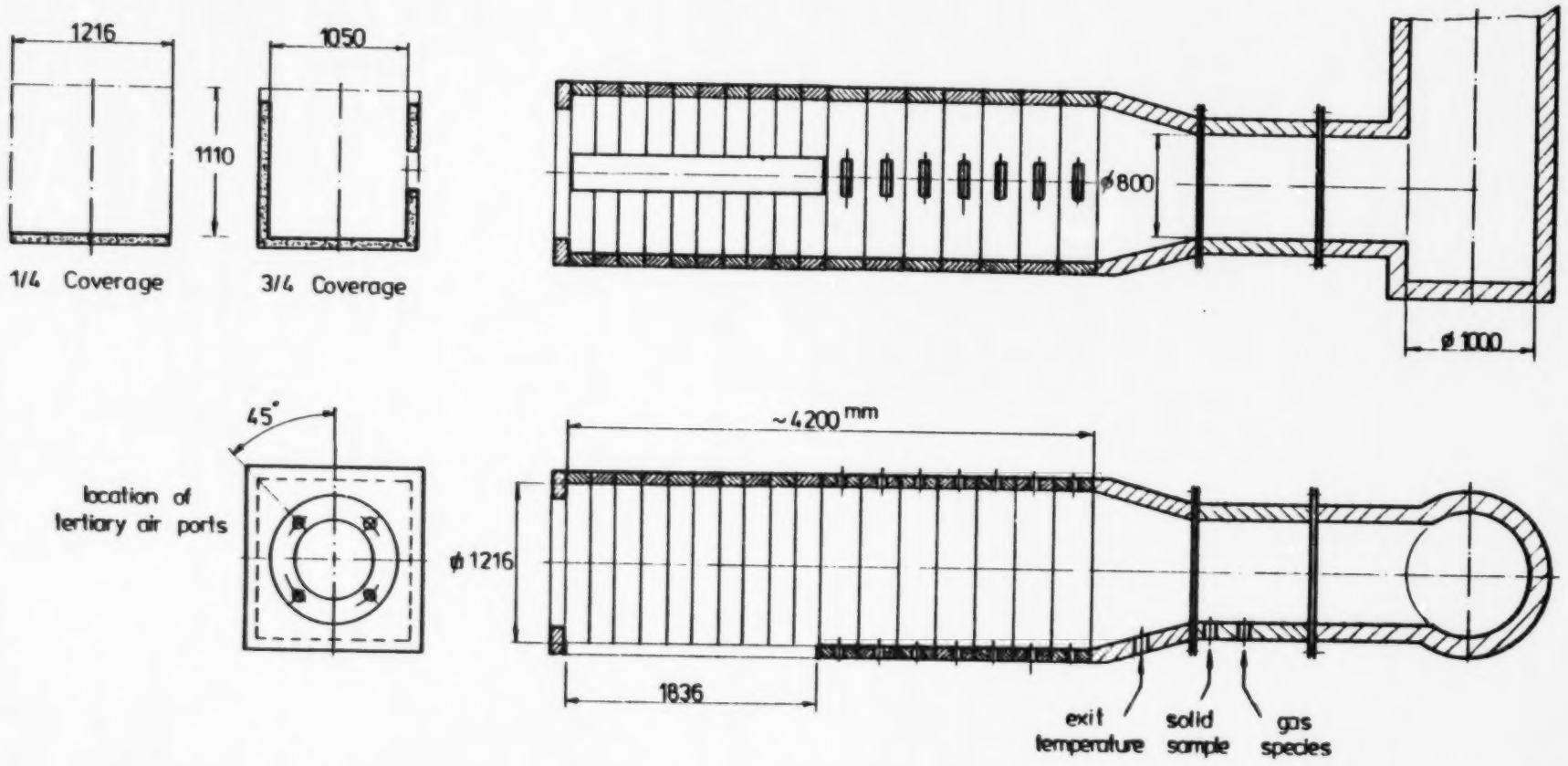
TABLE 13: Solids concentration and burnout at various radial positions in the flue gas duct.

Slurry	Coal type	Size distribution % <75 μm	Atomizing air required $\dot{m}_{atm}/\dot{m}_{f}$	Maximum turndown	Unsupported ingition with cold combustion air	Mean T_x %
A	mvb	91	17	3/1	yes	95
B	lvb	91	28	na	no	95
C	hvb	79	26	na	no	98
D	hvb	88	15	2/1	yes	98
E	hvb	72	14	3/1	yes	98
F	mvb	77	14-24	na	na	93
G	hvb	94	25	2/1	Borderline	95

na - not attempted

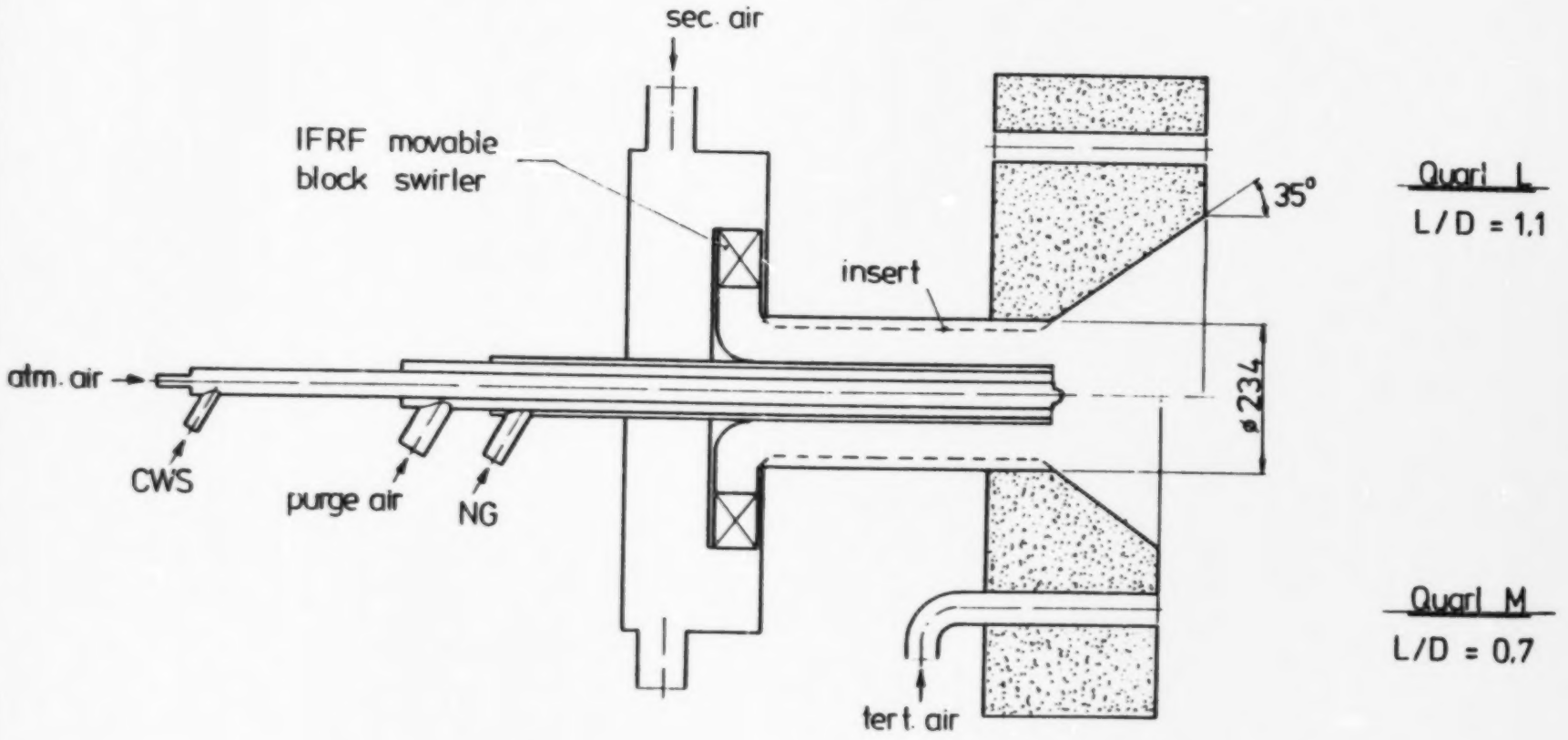
TABLE 14- SUMMARY OF THE SLURRIES COMBUSTION PERFORMANCE

FIGURES



IFRF

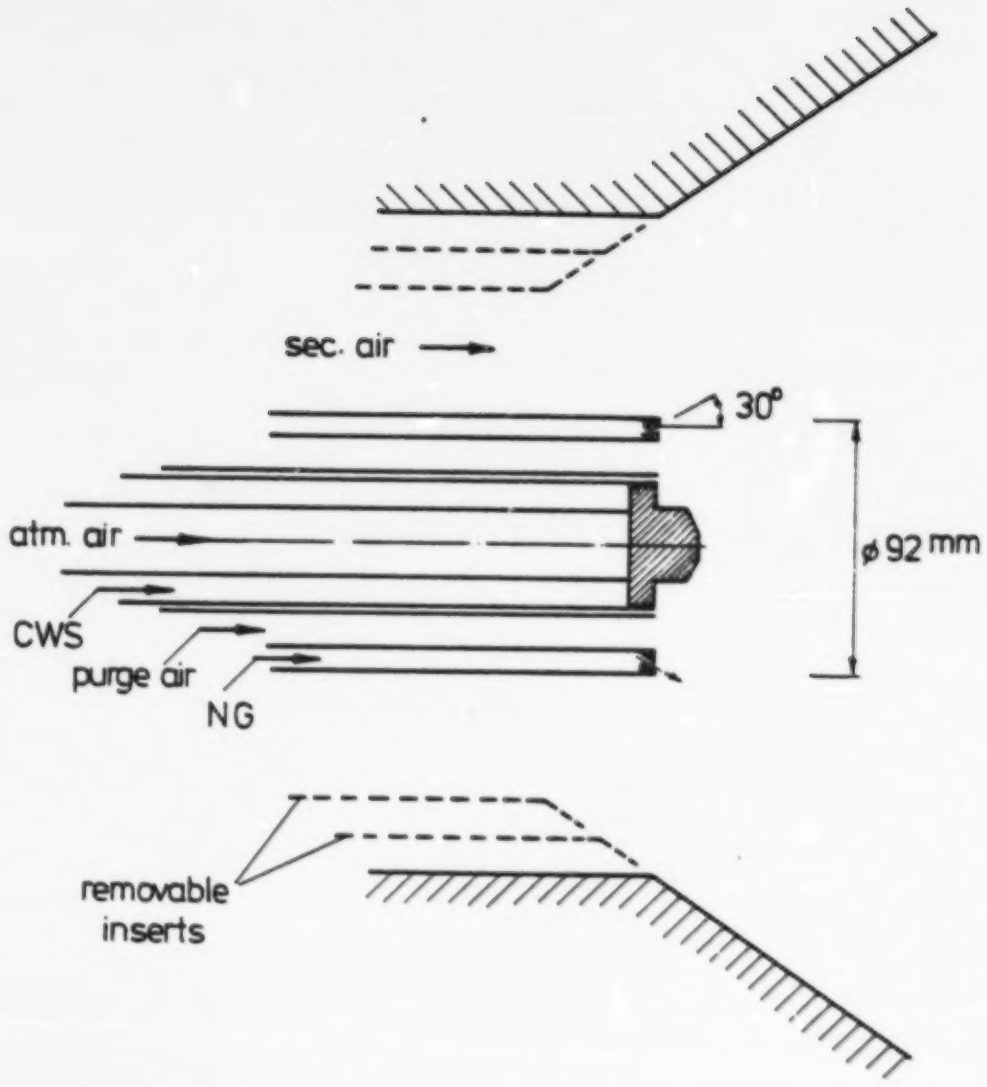
Fig: 1 IFRF watercooled furnace no: 2 with 17 segments



IFRF

84-0006

Fig: 2 Schematic of the experimental burner



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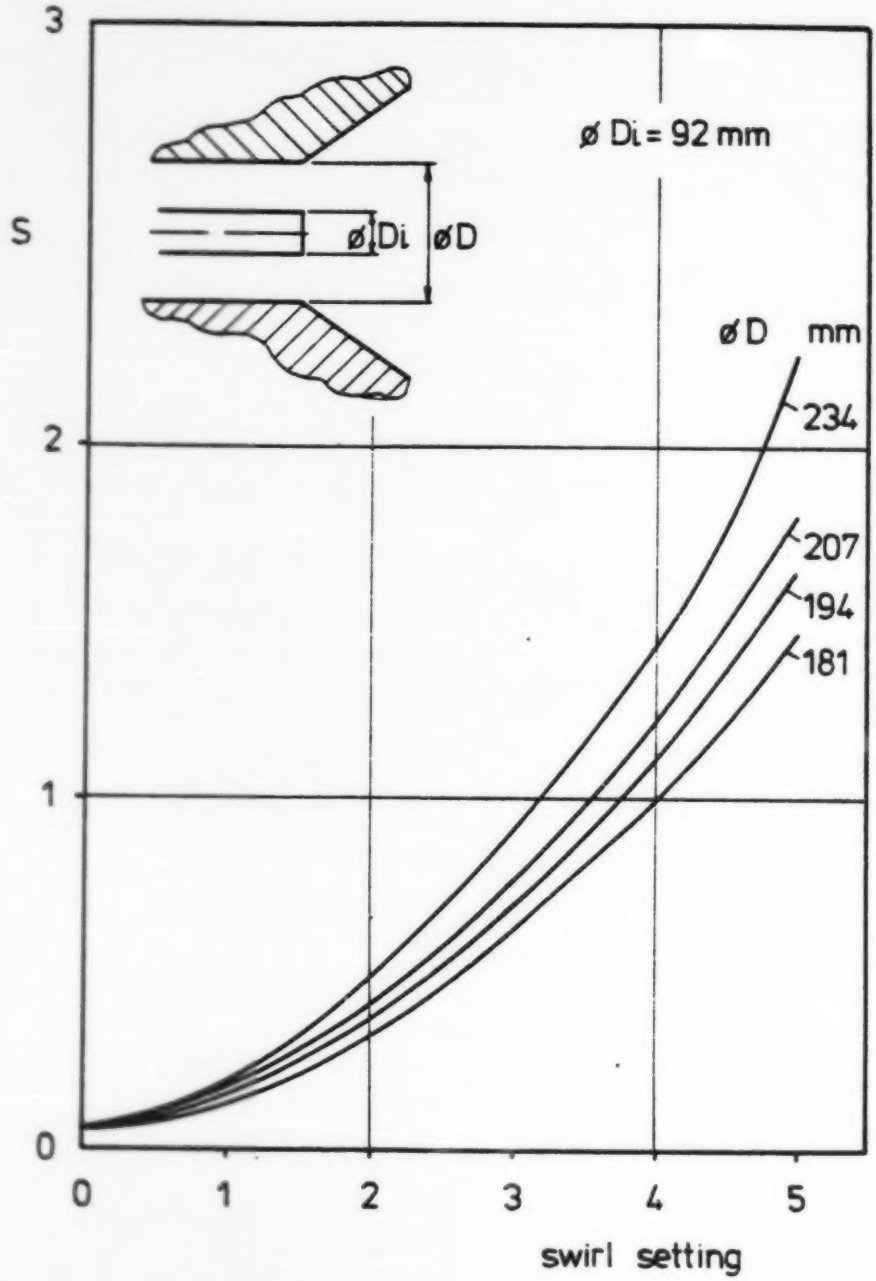
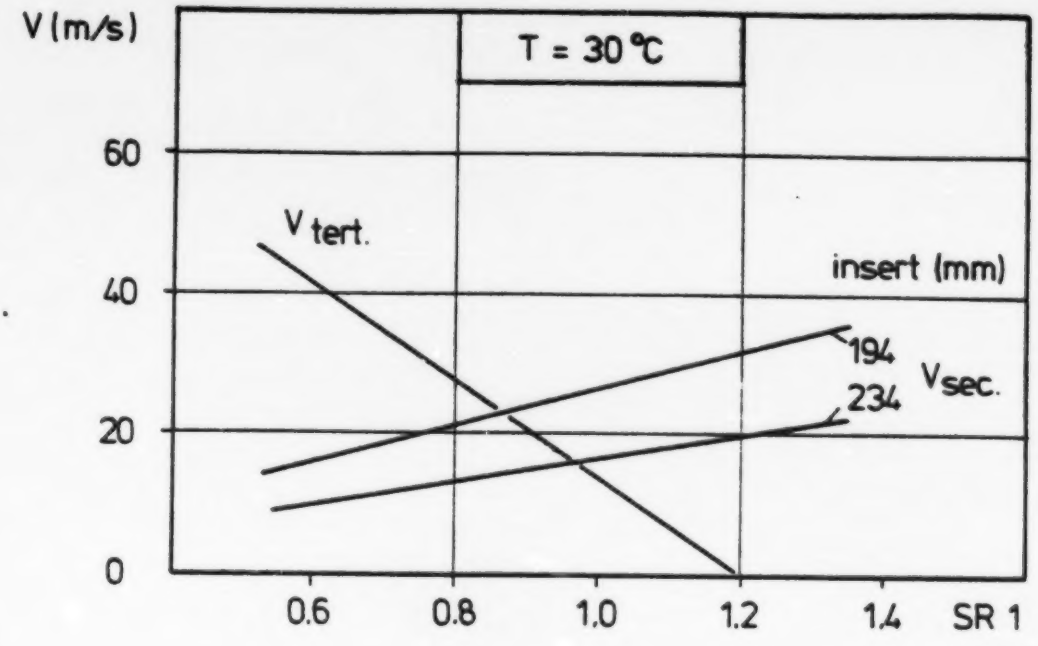
84-0007

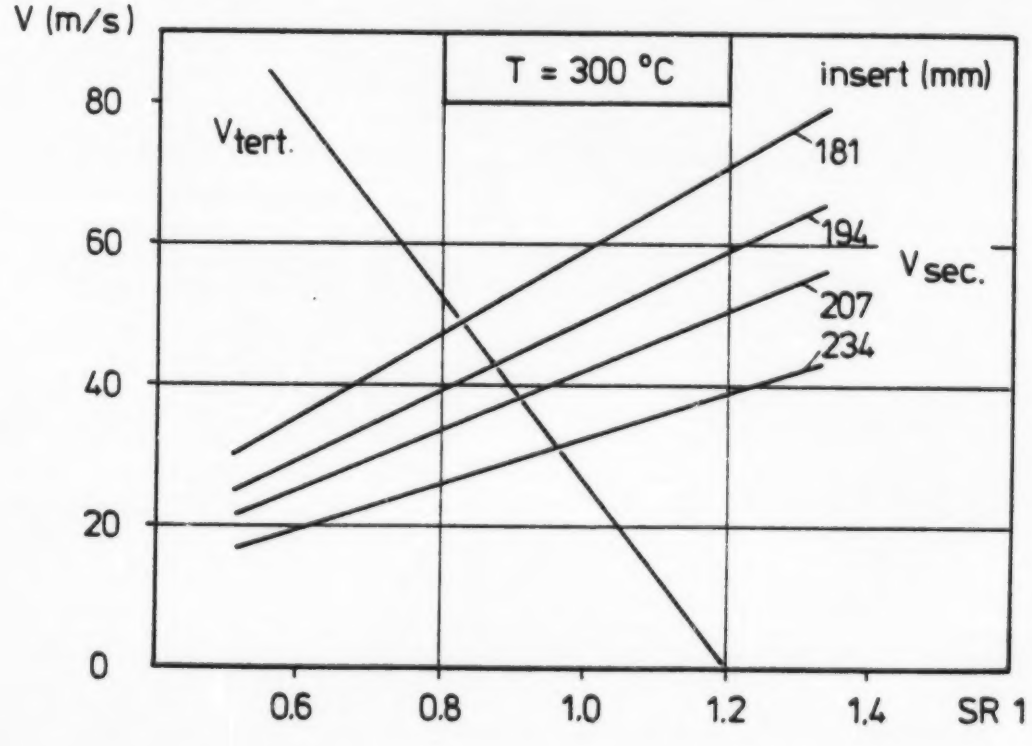
Fig: 3 .CWS gun and gassupport gun



IFRF

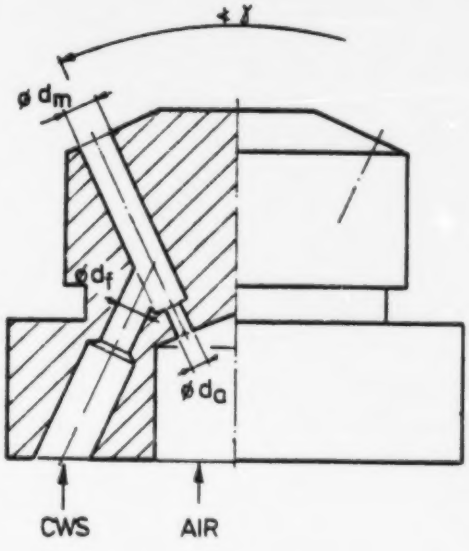
Fig: 4 Swirl number of secondary air flow with IFRF movable block swirler



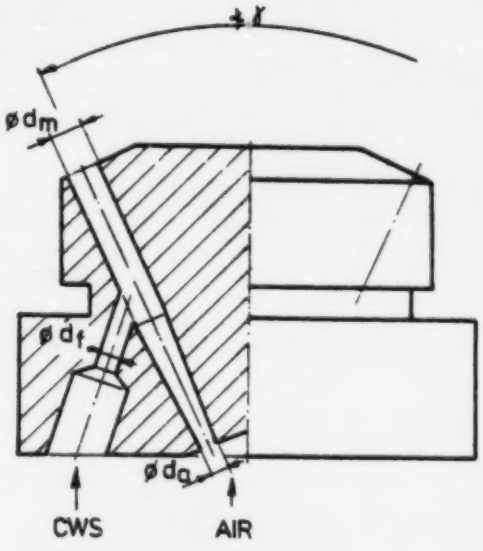


IFRF

Fig: 5 Throat velocities for secondary and tertiary air streams.



Standard Y - jet



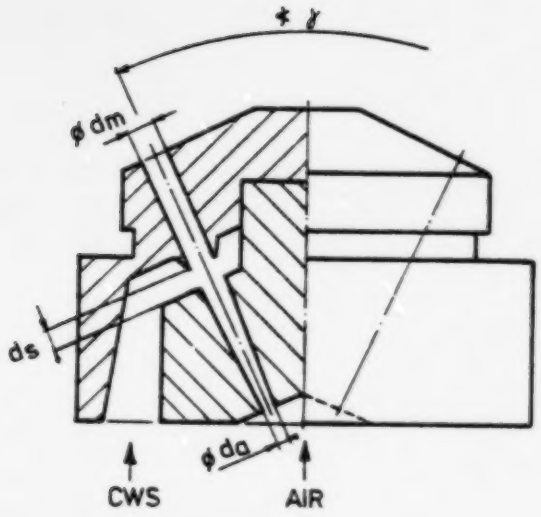
Divergent Y - jet

label	ø d_a	ø d_f	ø d_m	γ	no. of holes
CY-6	1.4	2.2	2.5	40°.50°.60°	6
CY-6L	1.4	2.5	2.8	40°.50°.60°	6
CY-8	1.2	2.2	2.5	50°	8
CY-10	1.1	2.0	2.2	50°	10

label	ø d_a	ø d_f	ø d_m	γ	no. of holes
CDY-6	1.4	2.5	2.8	40°.50°	6
CDY-8	1.2	2.2	2.5	50°	8
CDY-10	1.1	2.0	2.2	50°	10

IFRF

Fig: 6 Y - jet atomizers

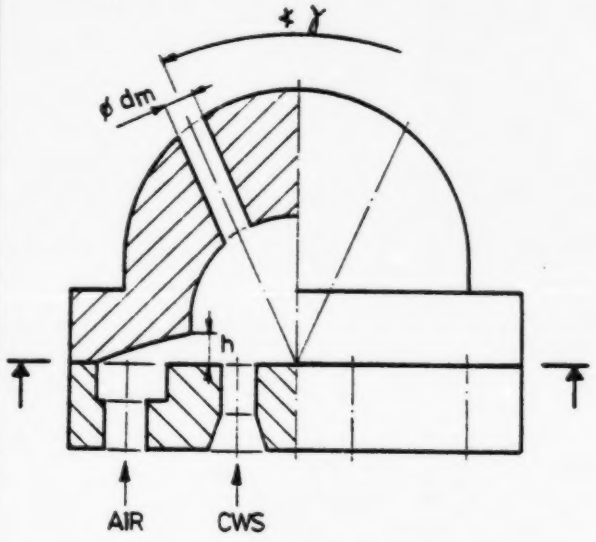


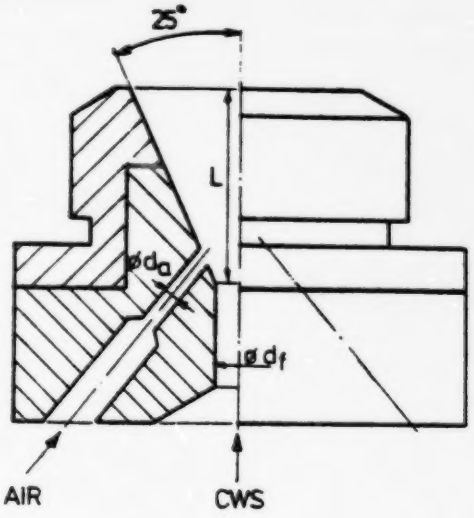
T - jet

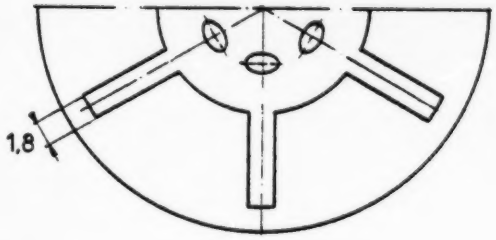
label	ϕ d_a	d_s	ϕ d_m	γ	holes
CT - 8	1.1	1.4	2.2	50°	8
CT - 10	1.0	1.1	2.2	50°	10

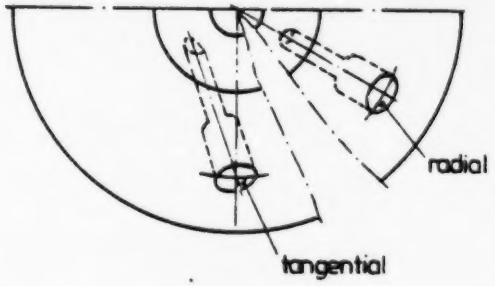
IFRF

Fig: 7 T - jet atomizers









Internal Mix

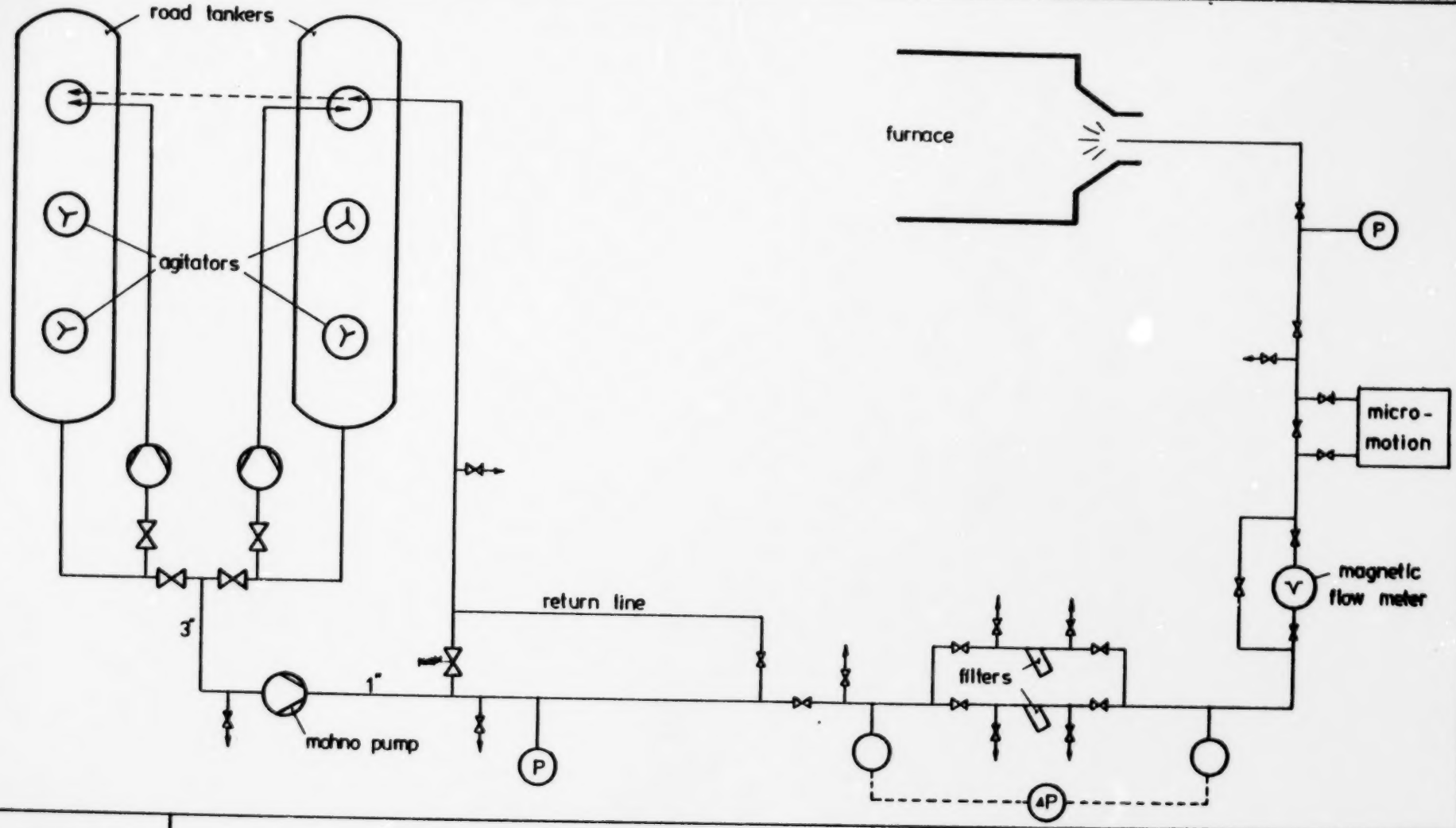
Single Hole

label	h	ø d_m	γ	no. of holes
IM S	2.24	2.05	40°.50°.60°	6
IM L	1.66	2.75	40°.50°.60°	6

label	ø d_a	ø d_f	injec-tion	L
SH	1.4	3.5	rad/tang.	7.5
SH E	1.4	3.5	rad/tang.	13.0

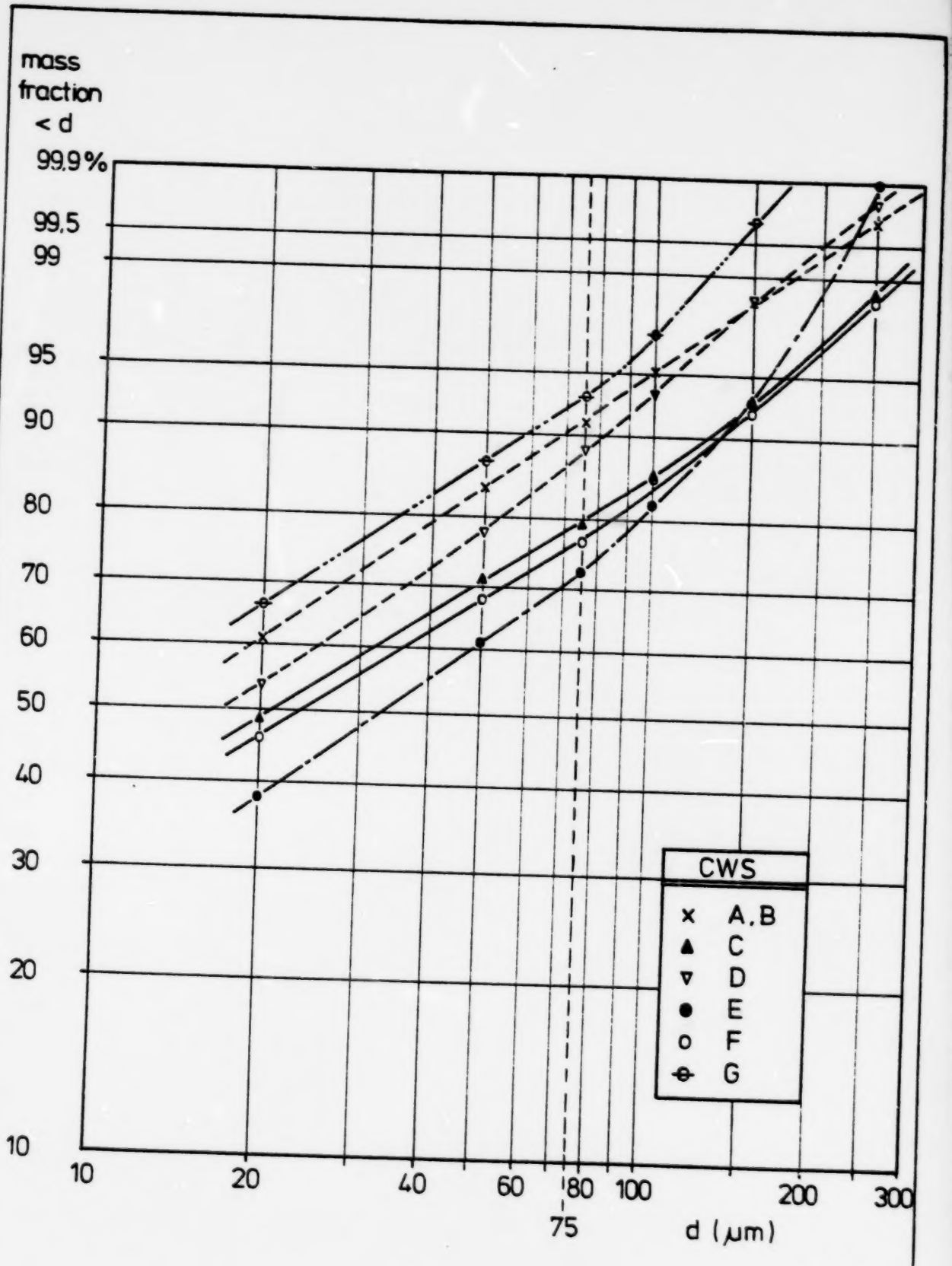
IFRF

Fig: 8 .IM and SH atomizers



IFRF

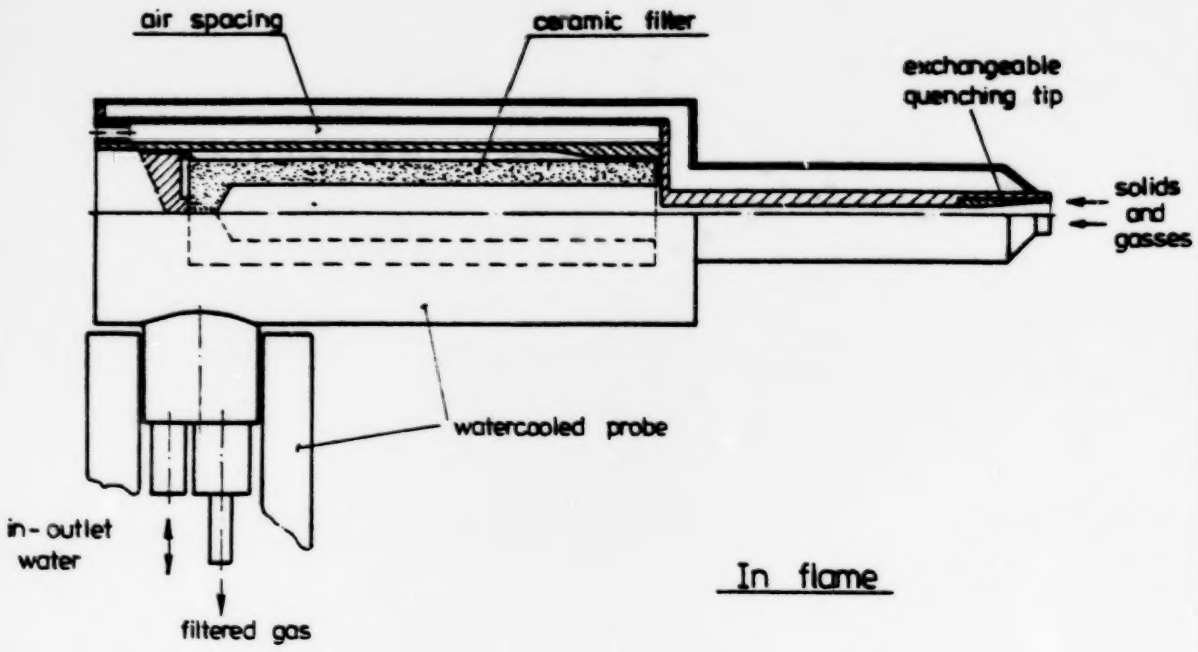
Fig: 9 Schematic set-up of the CWS handling system

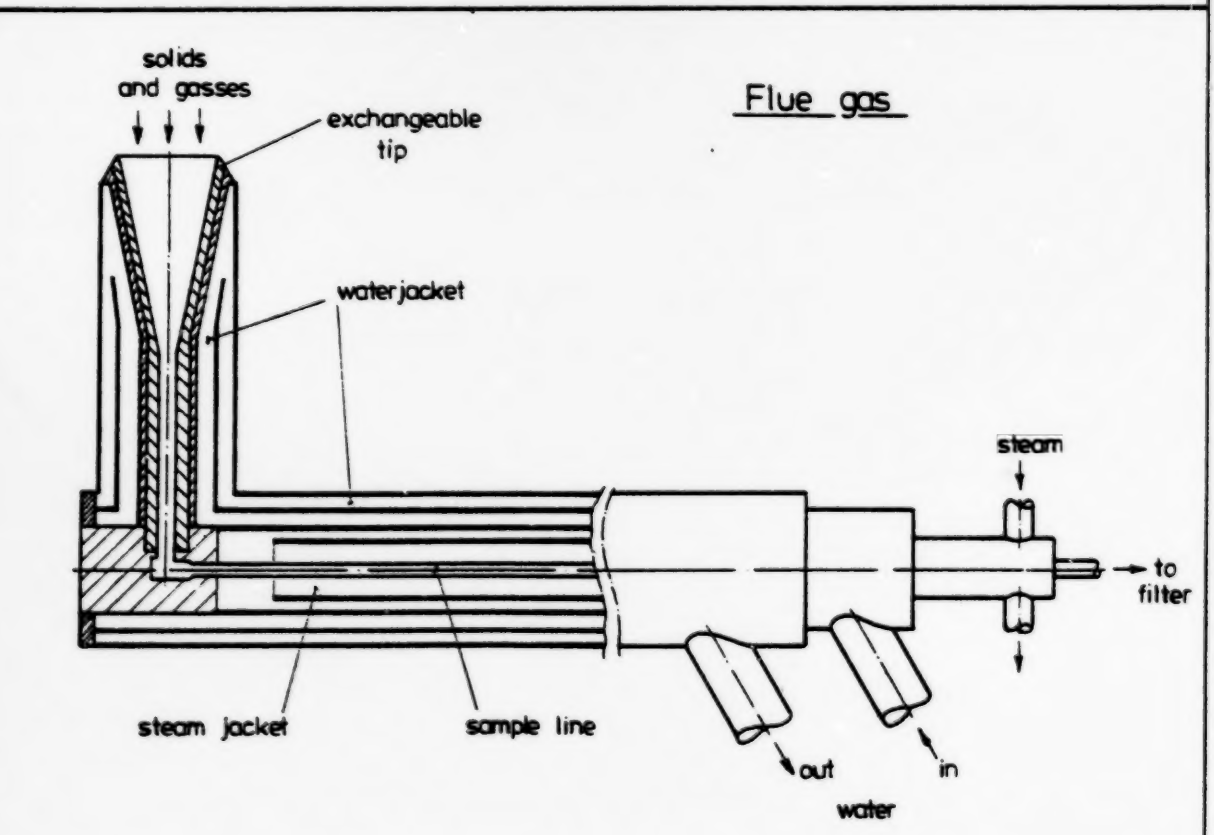


IFRF

84 - 0079

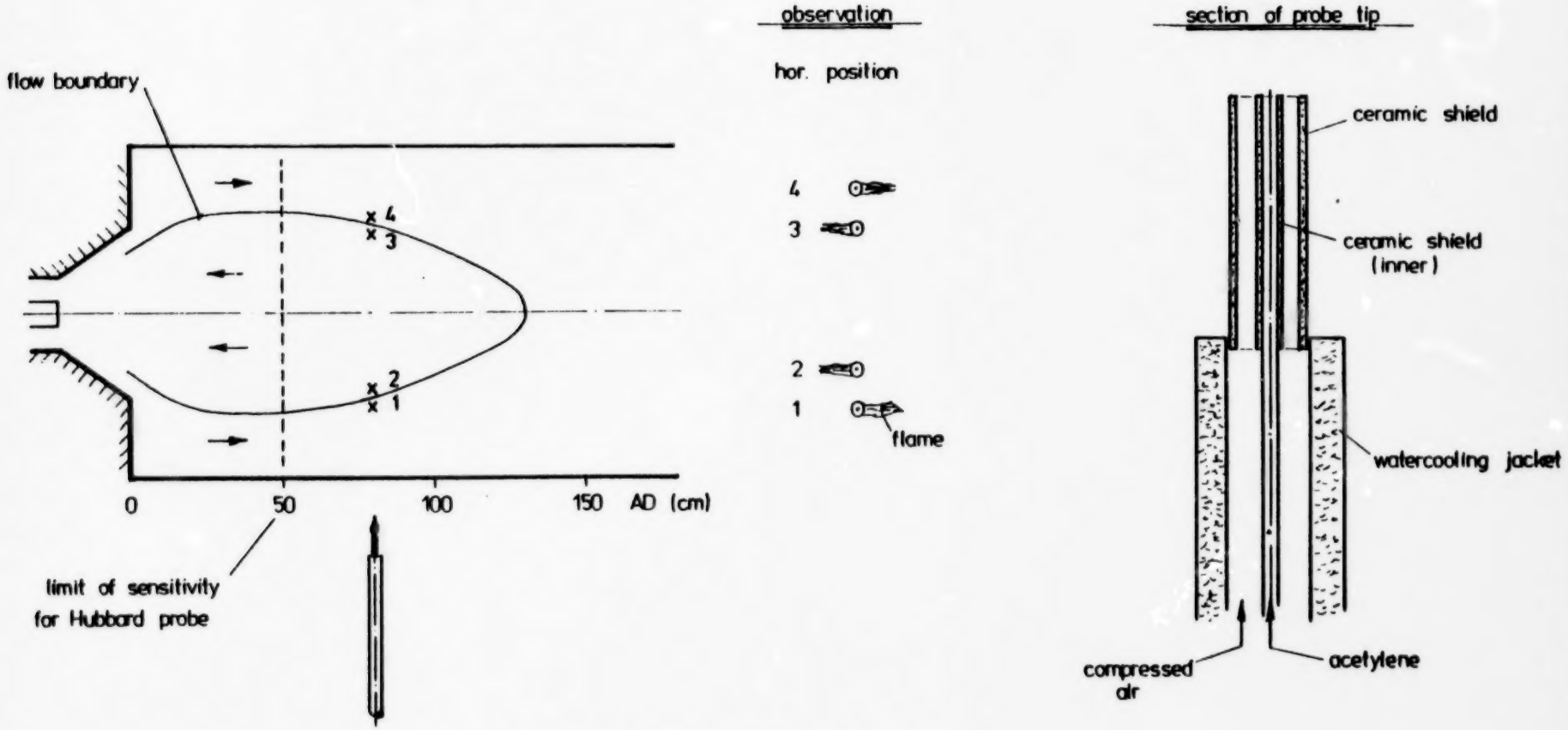
Fig: 10 Particle size distributions
wet sieve technique





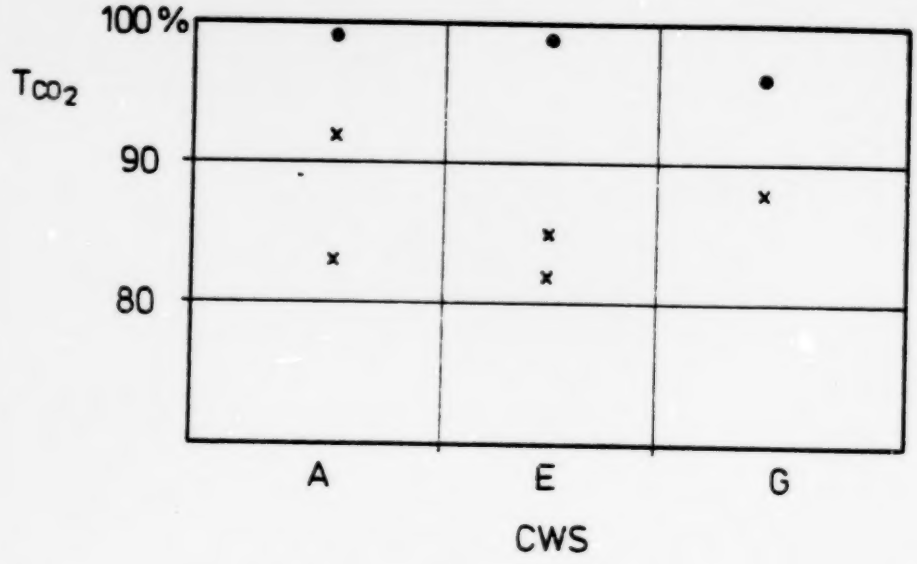
IFRF

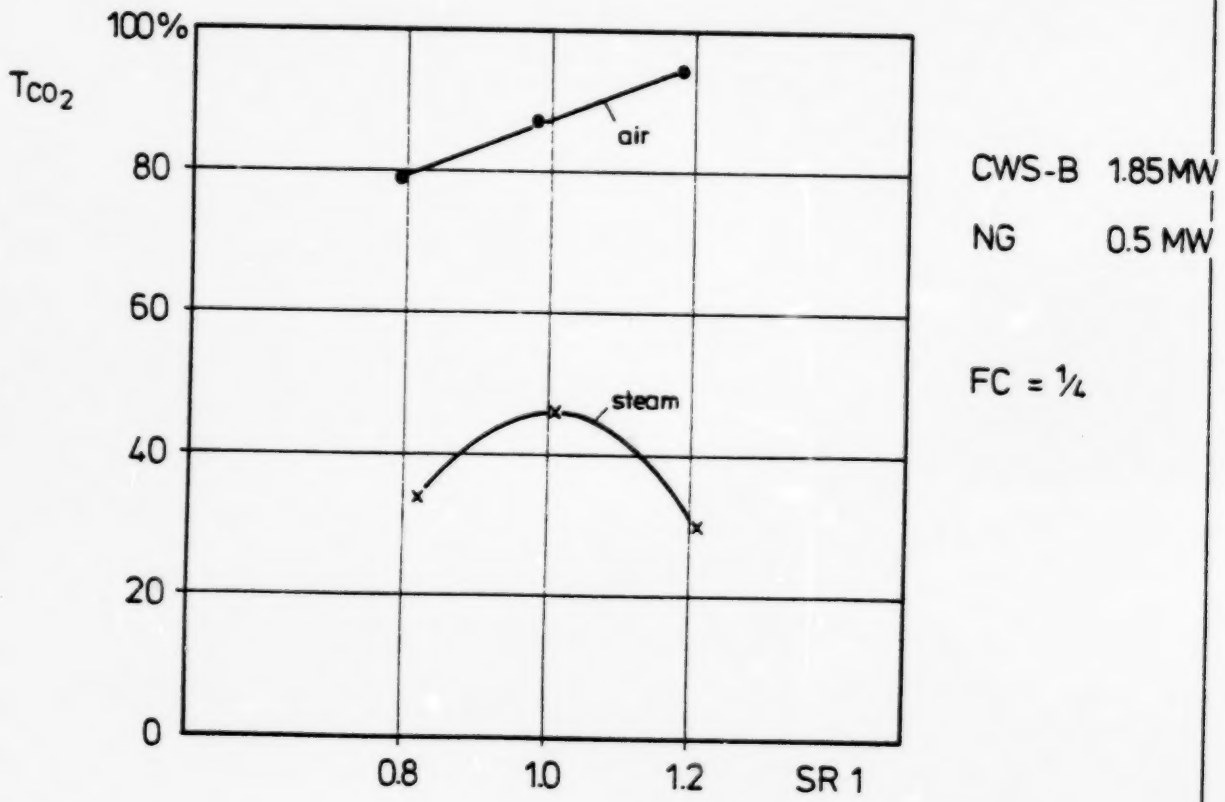
Fig: 11 Sample probes for in - flame and flue solids



IFRF

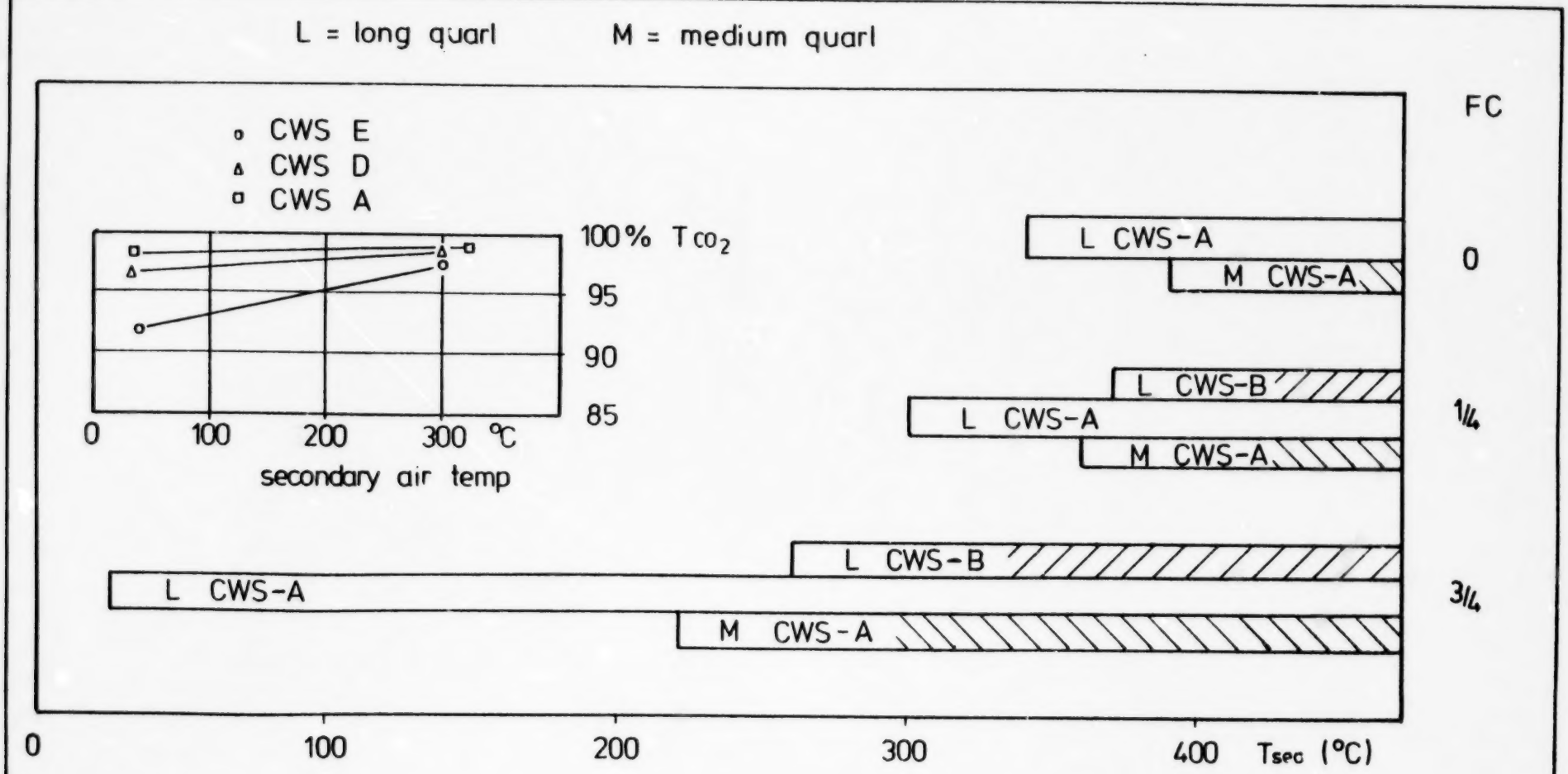
Fig: 12 Schematic of Schreier probe and method of operation





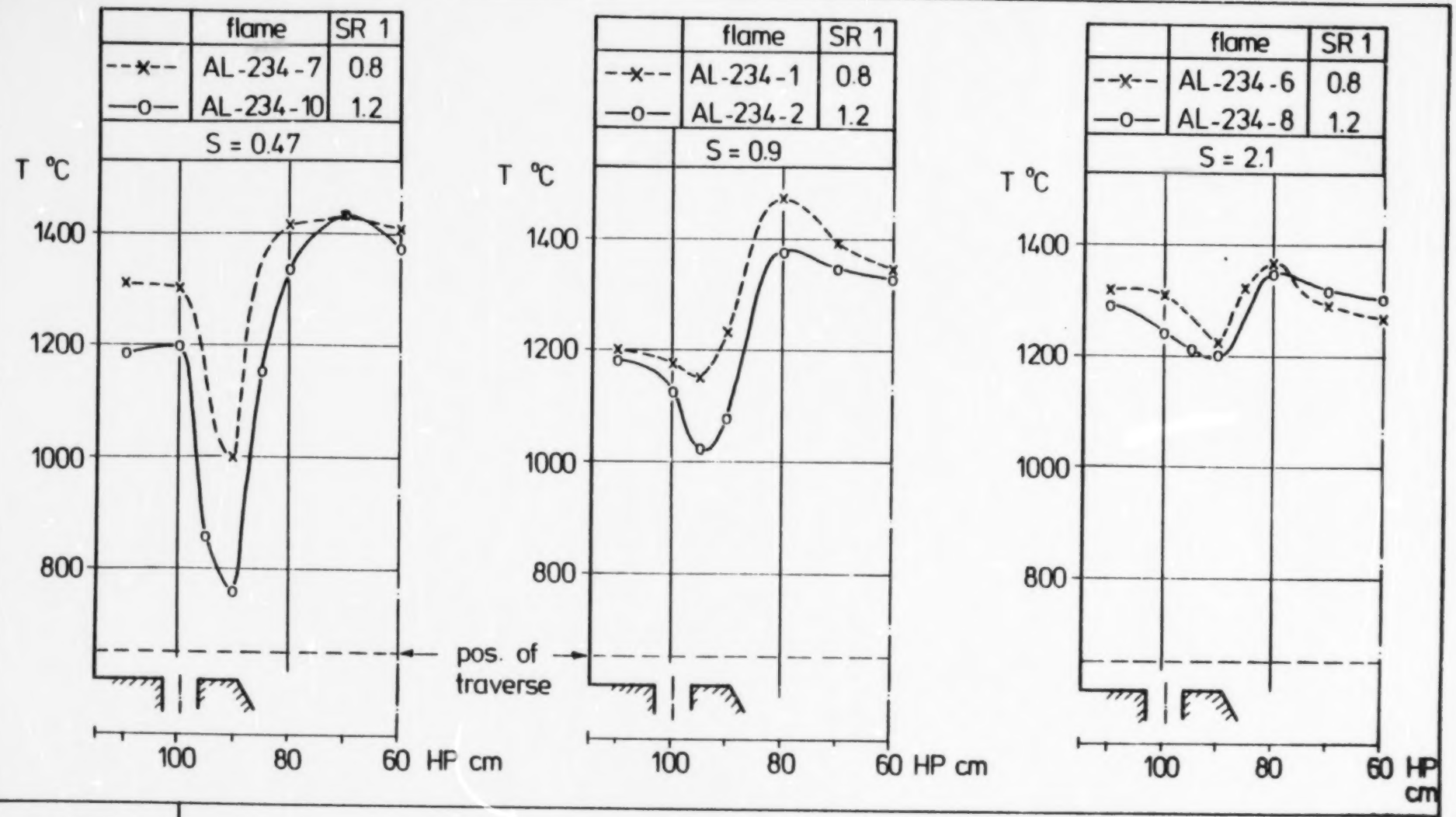
IFRF

Fig: 13 Maximum CWS burnout
air / steam atomization
CWS - A, B, E, G



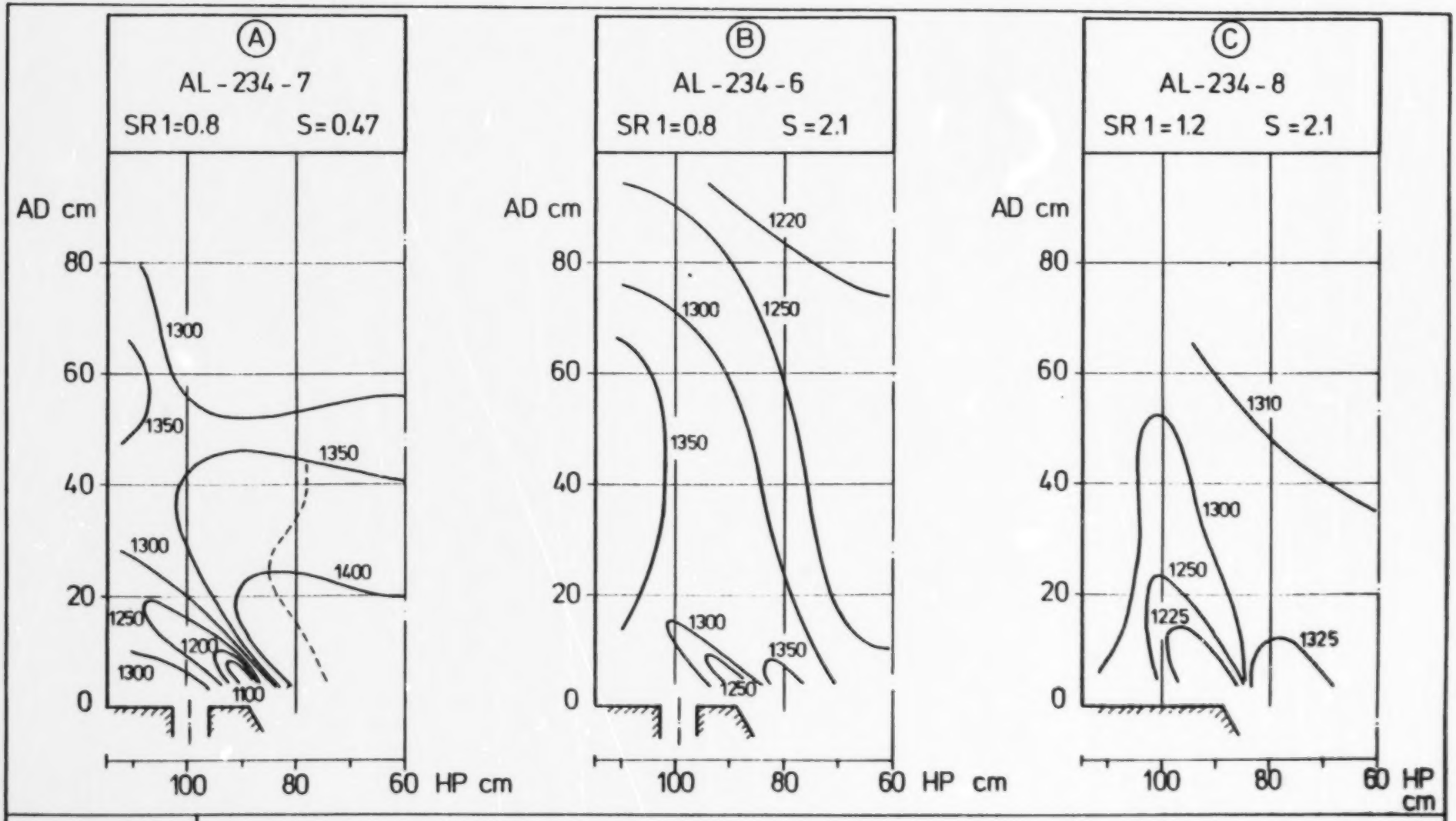
IFRF

Fig.14: Minimum secondary air temperature required for unsupported combustion ; CWS-A, B



IFRF

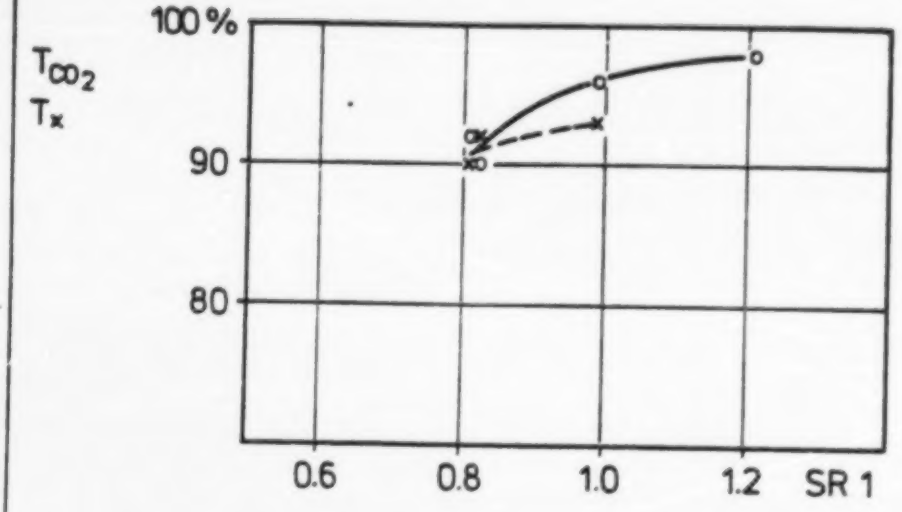
Fig. 15 Radial temperature profiles at AD 5
effect of staging CWS - A , FC = 3/4



IFRF

Fig: 16 Isotherms : effect of swirl and staging

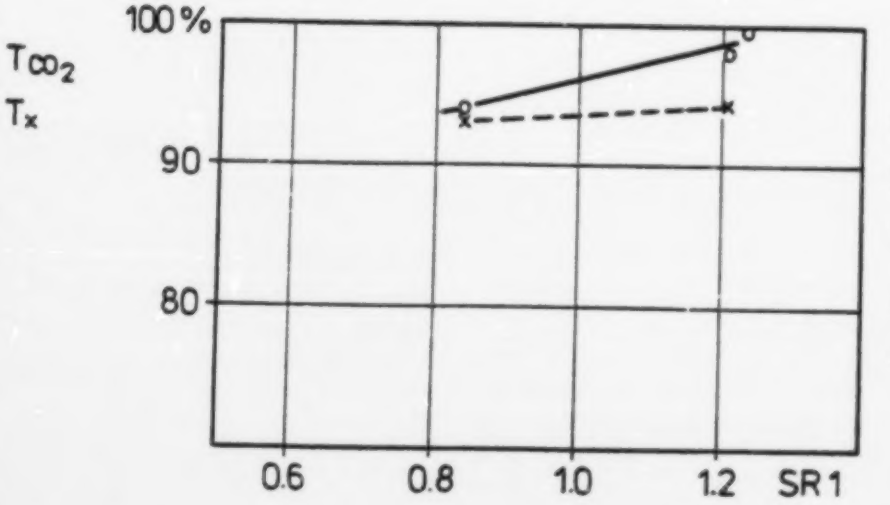
CWS - A . FC = 3/4



(A)

FC = 0
S = 0.9
$T_{sec.}$ = 450 °C
Atm. = CDY - 6
AFR = 20%

o T_{CO_2}
x T_x



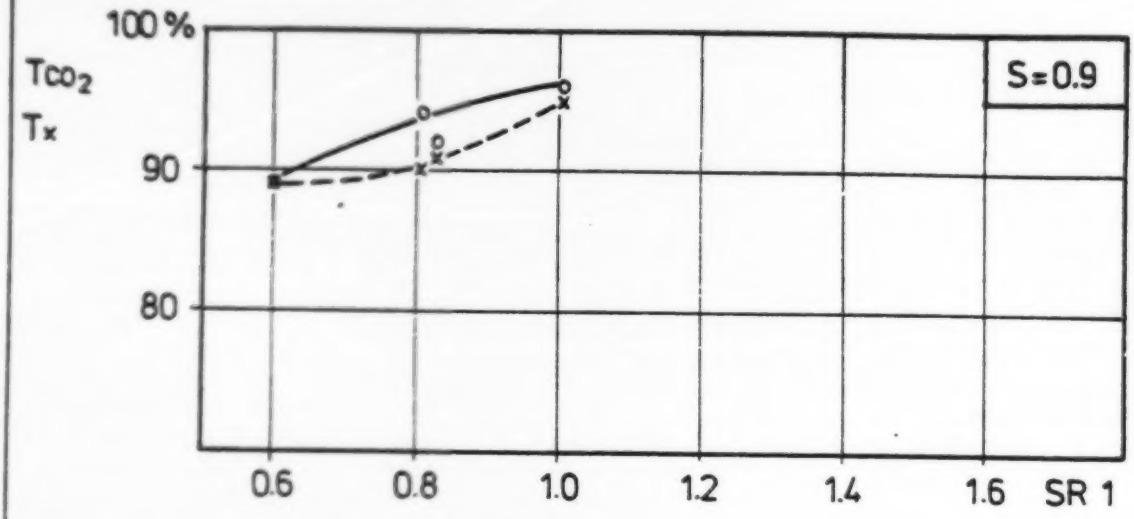
(B)

FC = ¾
S = 0.9
$T_{sec.}$ = 320 °C
Atm. = CY-6
AFR = 20%

IFRF

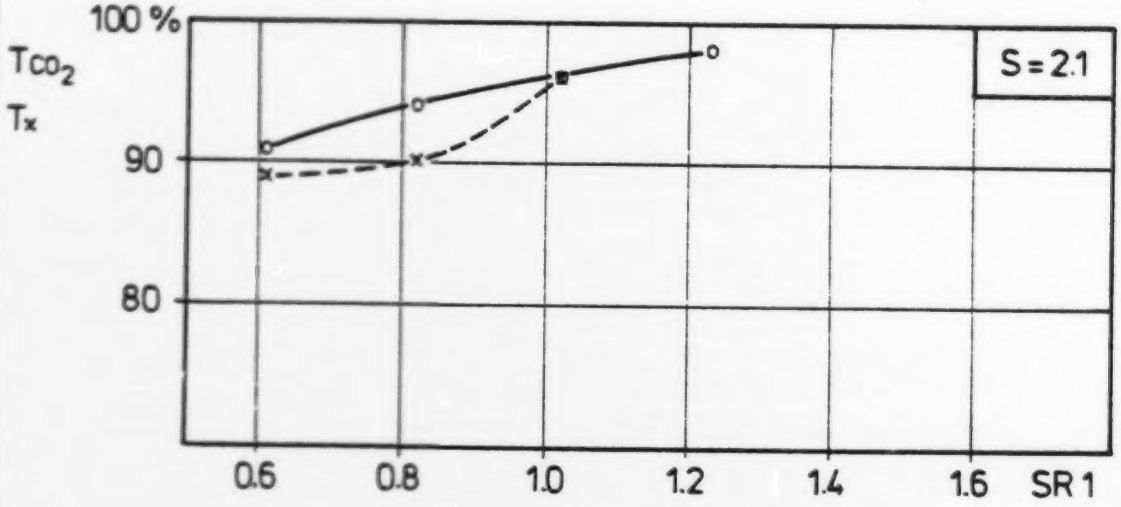
Fig: 17 Burnout versus SR 1

CWS-A



o T_{CO_2}
x T_x

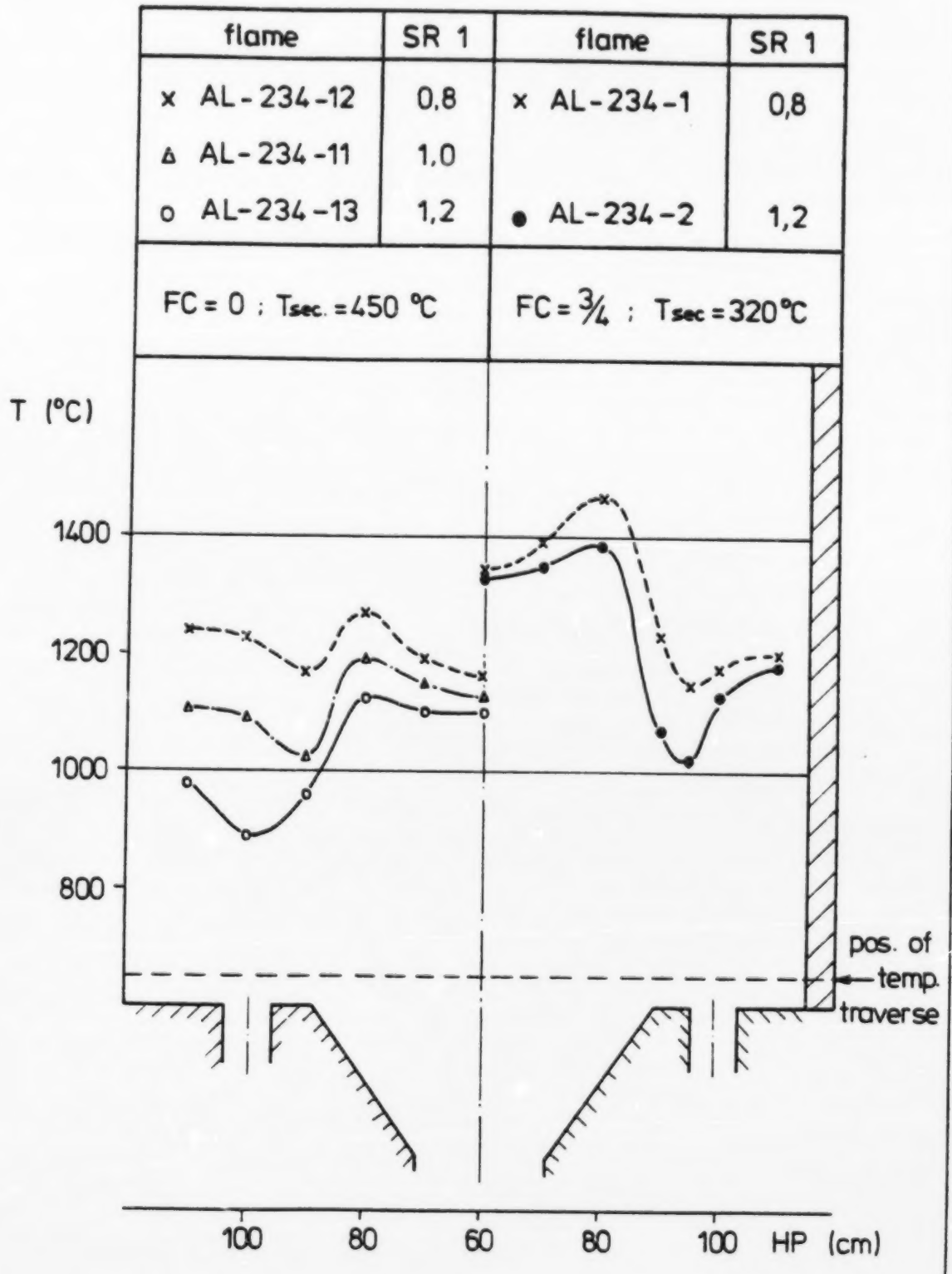
Atomizer	CDY - 8
AFR	20 %
$T_{sec.}$	300 °C



IFRF

Fig: 18 Burnout as a function of SR 1

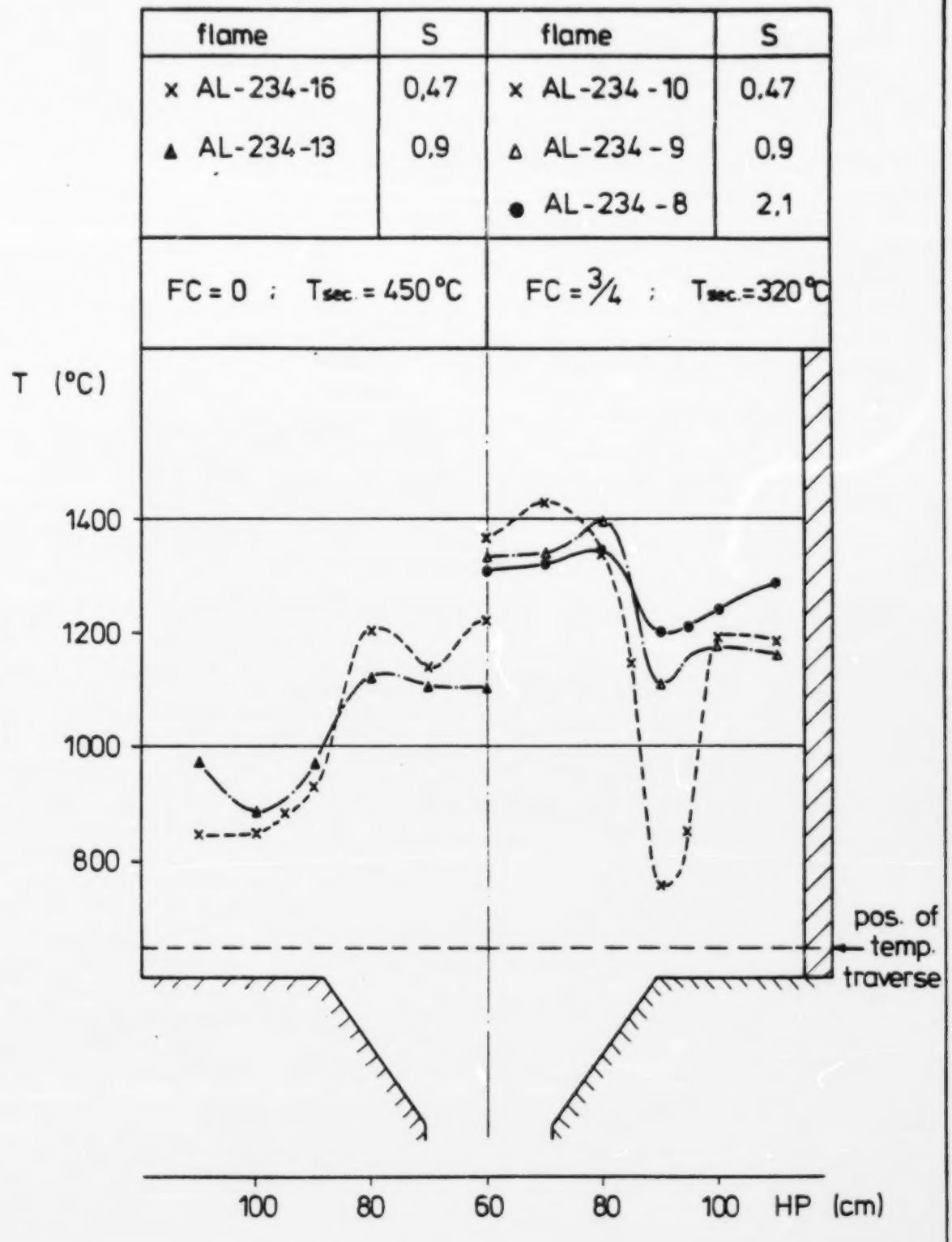
CWS-A . FC = ¼



IFRF

84-0018

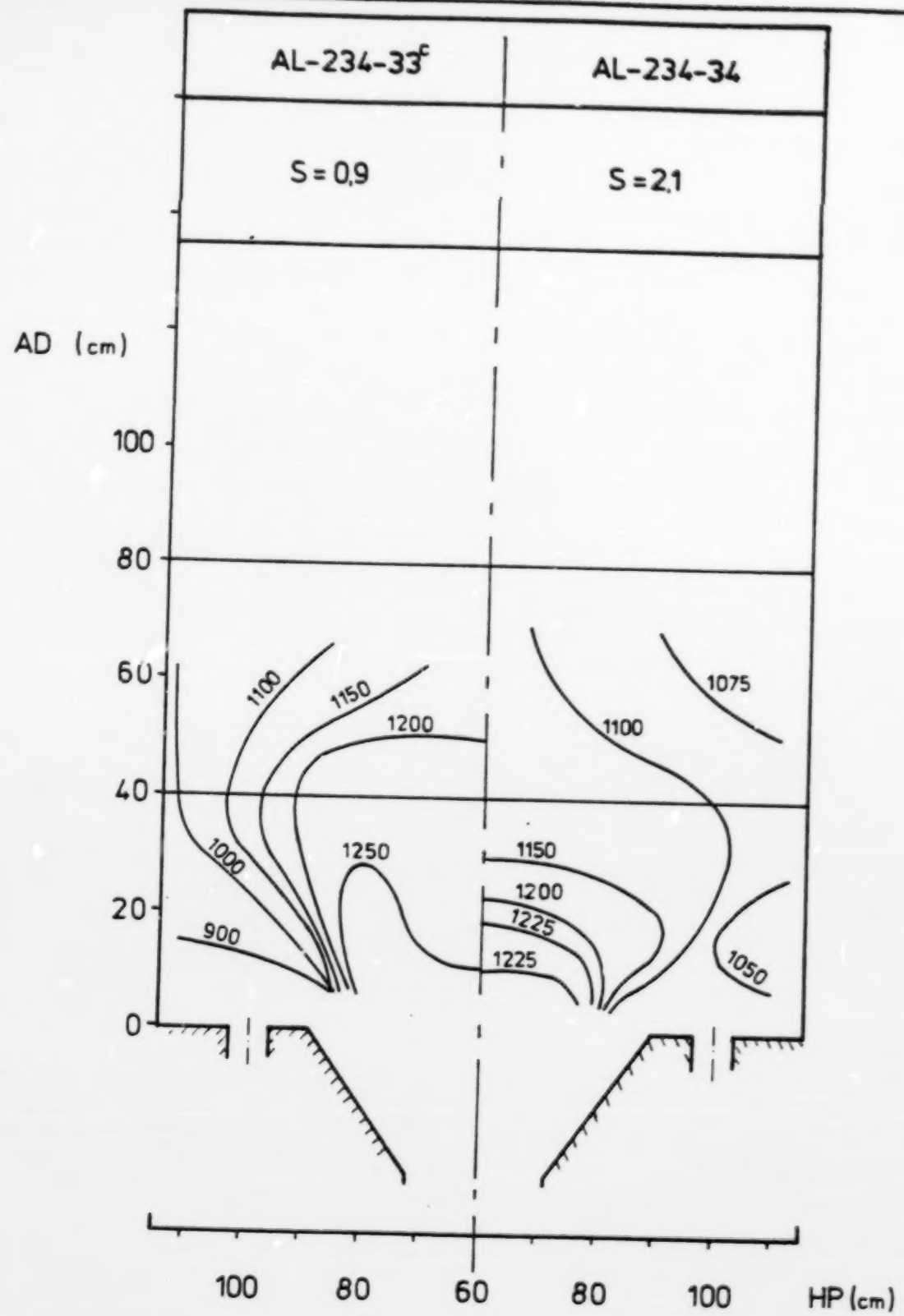
Fig: 19 Radial temperature profiles at AD 5
effect of staging : CWS - A
S = 0.9 ; FC = 0. 3/4



IFRF

84-0016

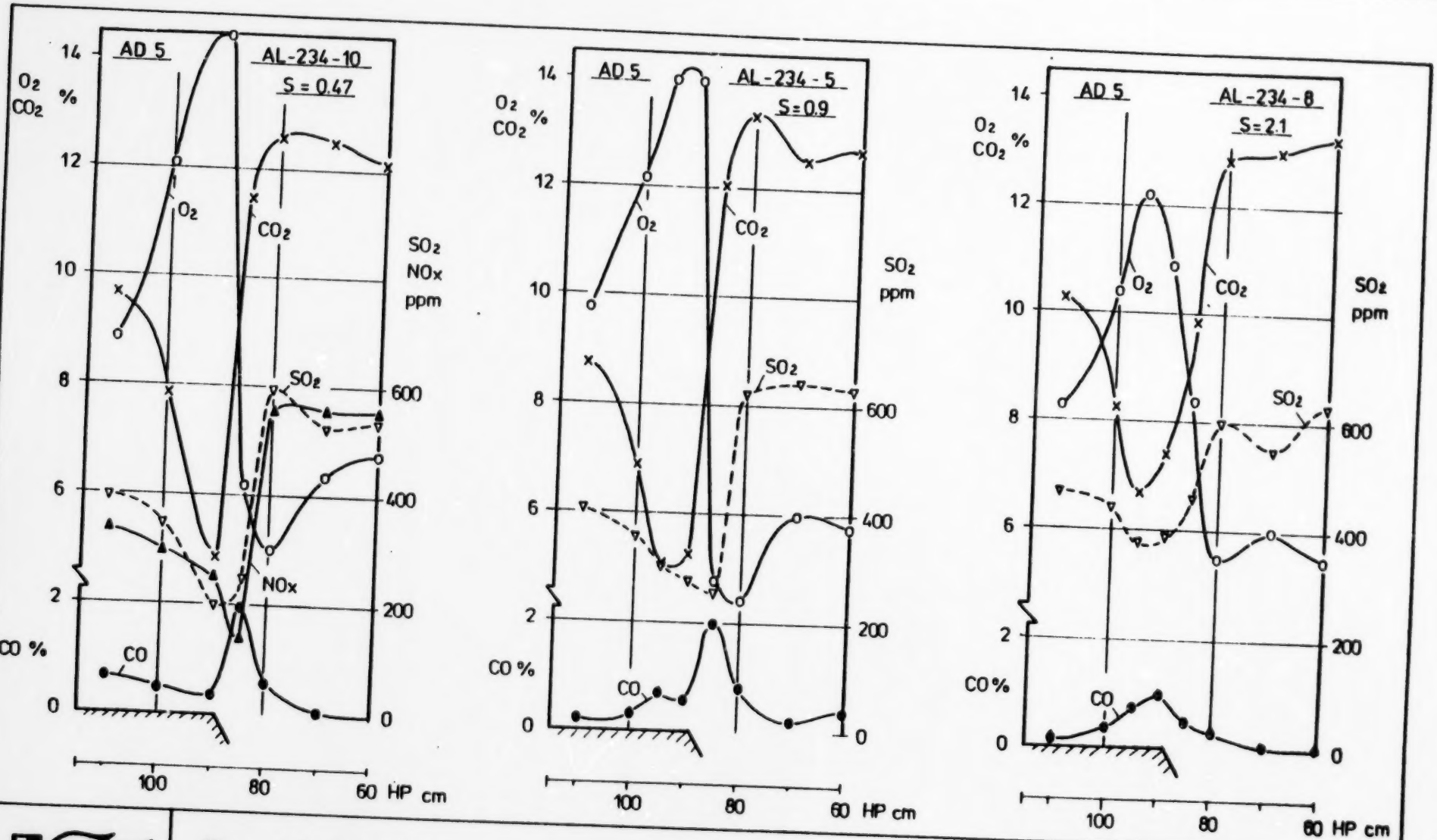
Fig: 20 Radial temperature profiles at AD 5
effect of swirl ; CWS - A
SR 1 = 1.2 FC = 0, 3/4



IFRF

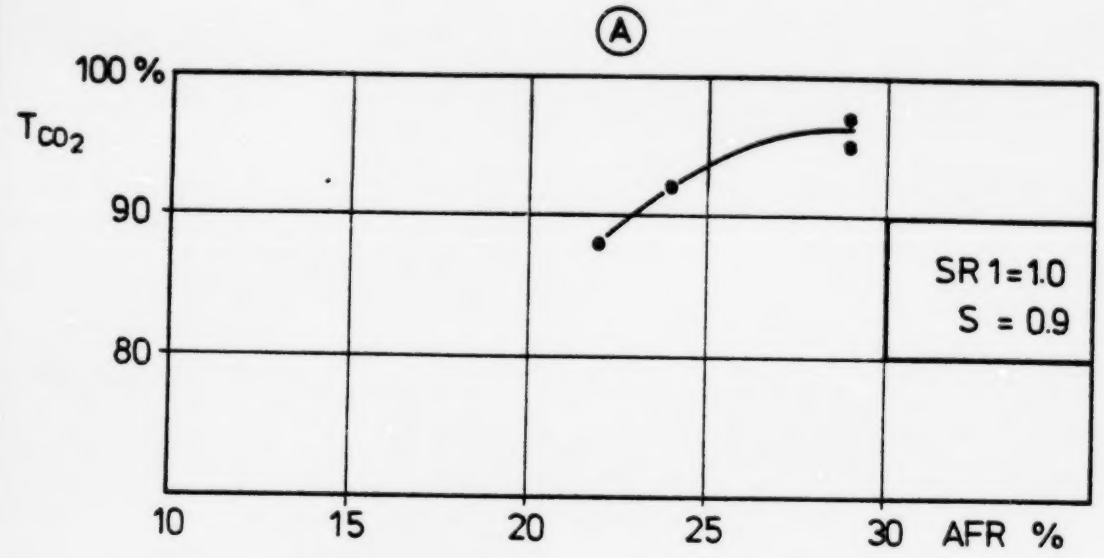
Fig: 21 .Isotherms : effect of swirl

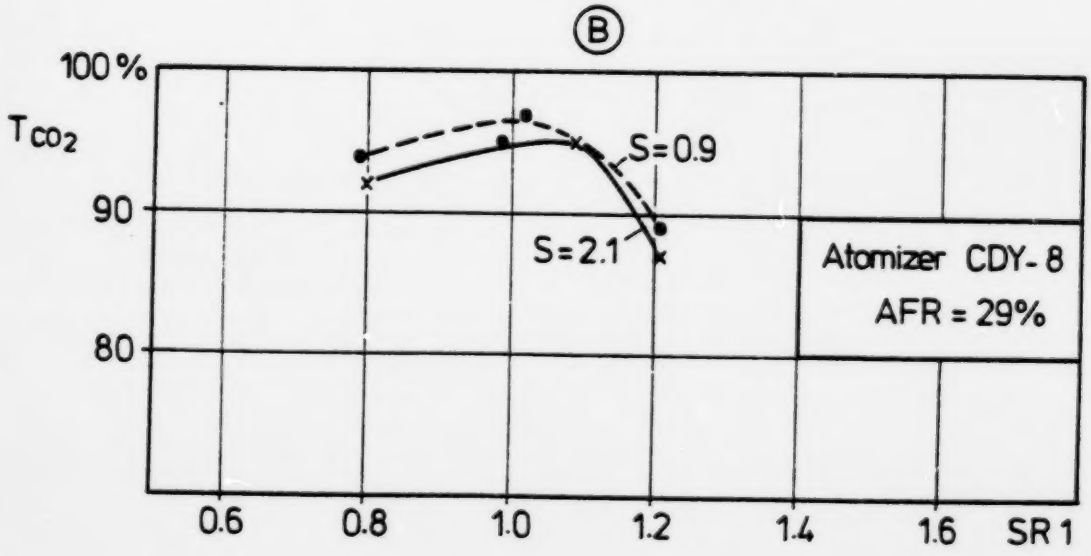
CWS - A , FC = ¼ , SR 1 = 0,8



IFRF

Fig: 22 Radial gasconcentration profiles at AD 5
effect of swirl CWS-A, SR1=1.2, FC = 3/4

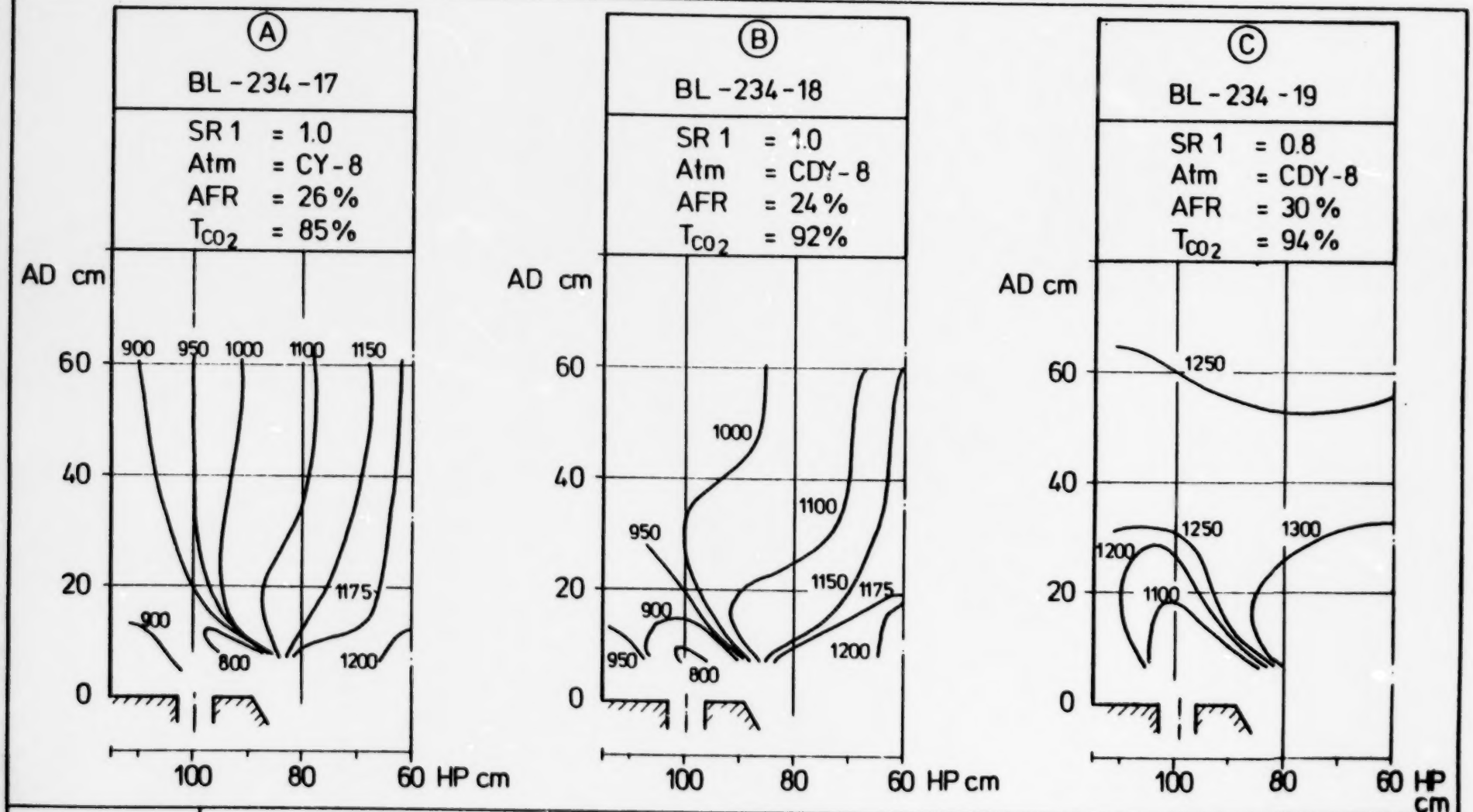




IFRF

Fig: 23 Burnout versus AFR and SR 1

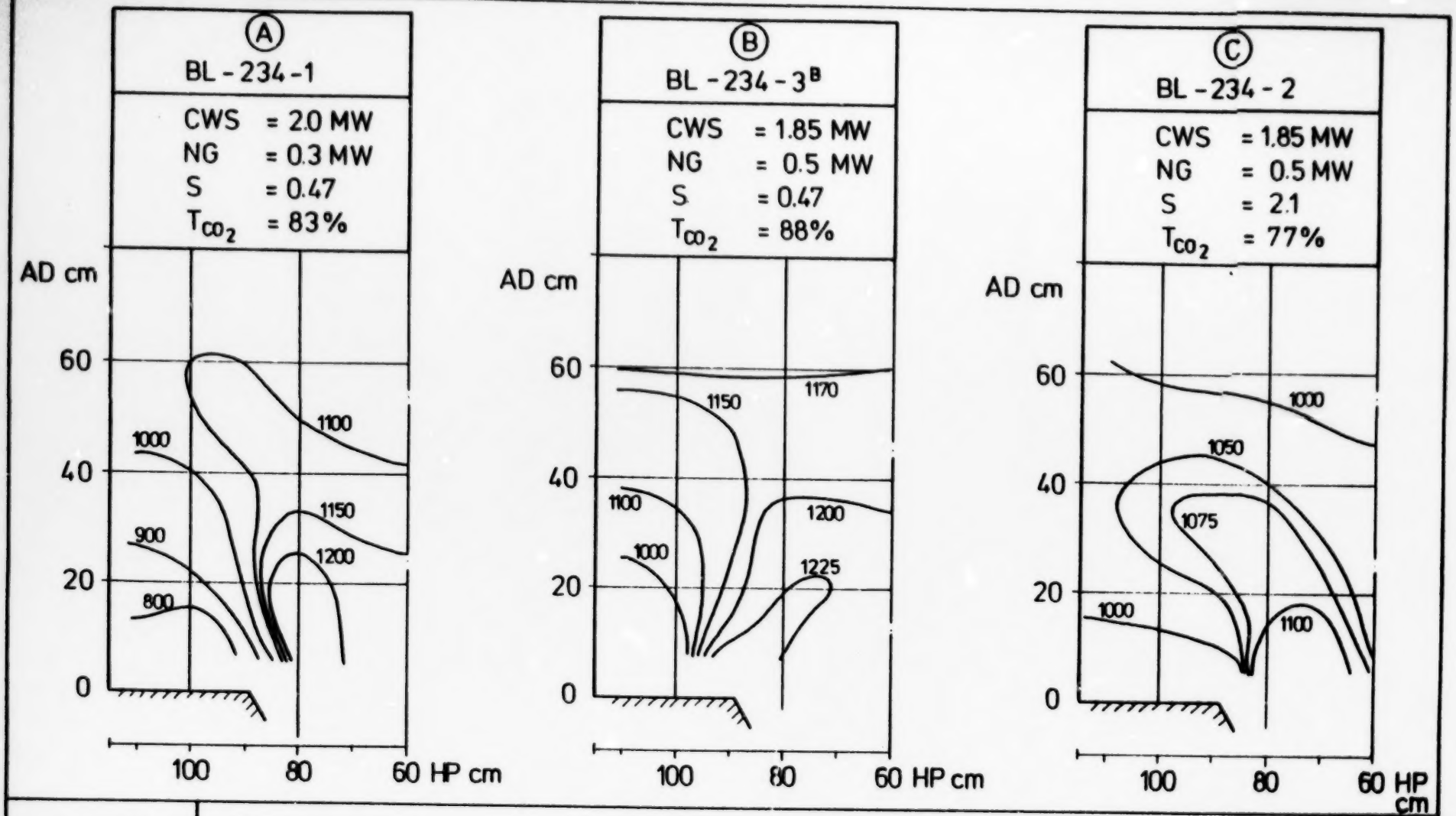
CWS - B . FC = 3/4



IFRF

Fig: 24 Isotherms ; effect of atomizer, AFR and SR 1

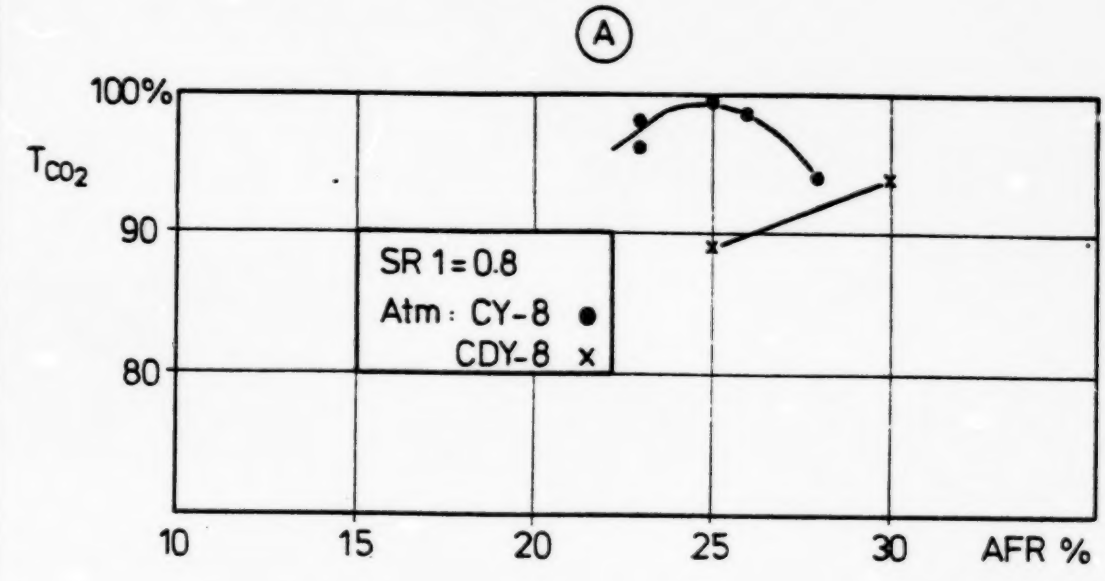
CWS - B . FC = 3/4 . S = 0.9

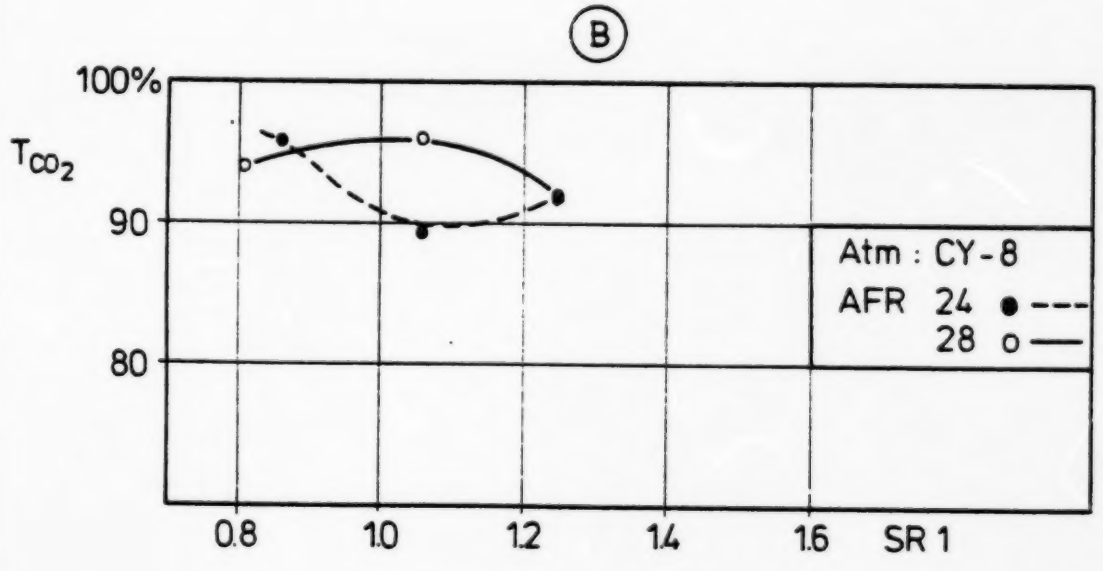


IFRF

Fig: 25 Isotherms for CWS - B / NG flames

effect of gassupport and swirl : FC = ¼ , SR 1 = 1.2

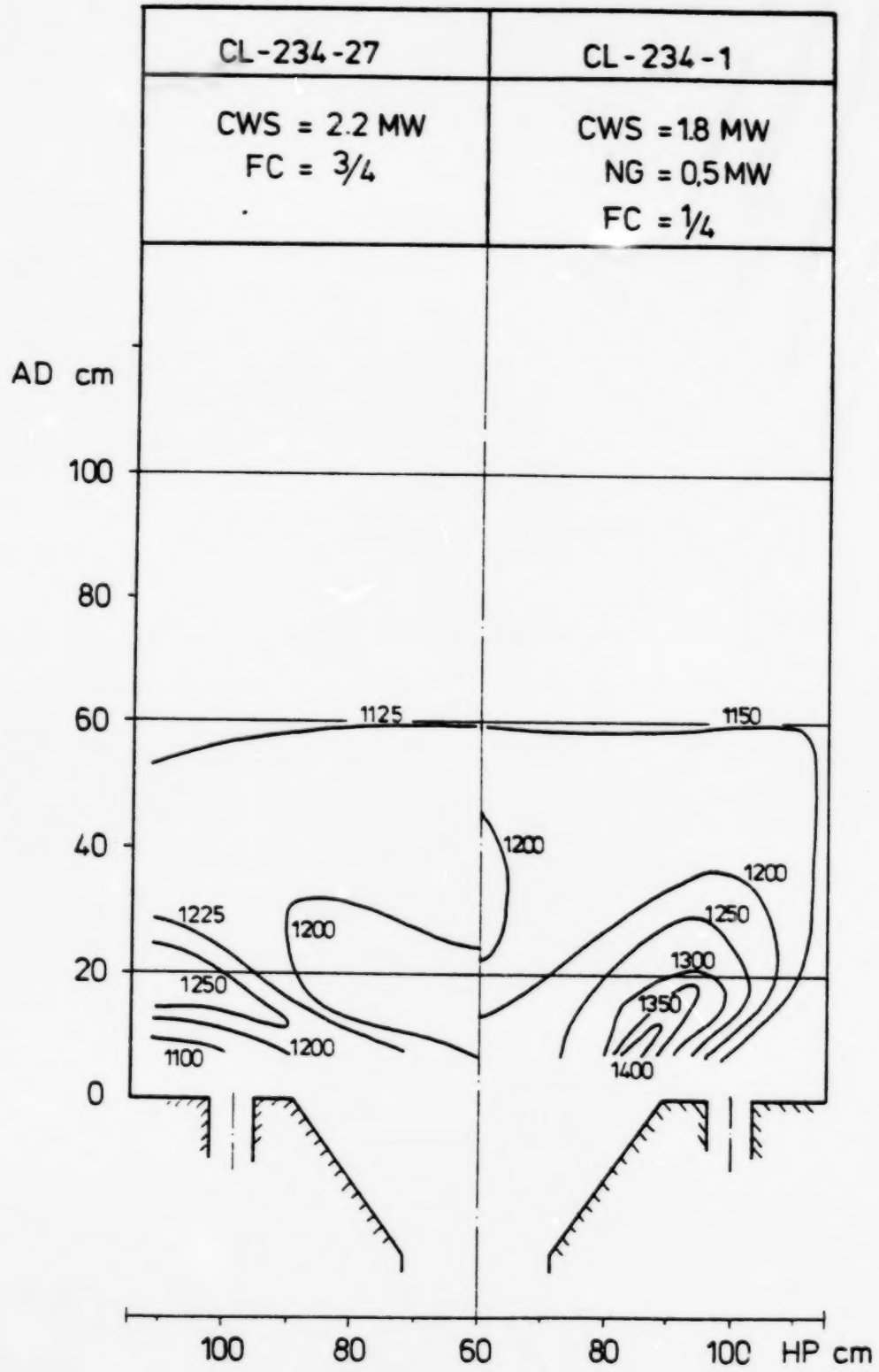




IFRF

Fig: 26 Burnout versus AFR and SR 1

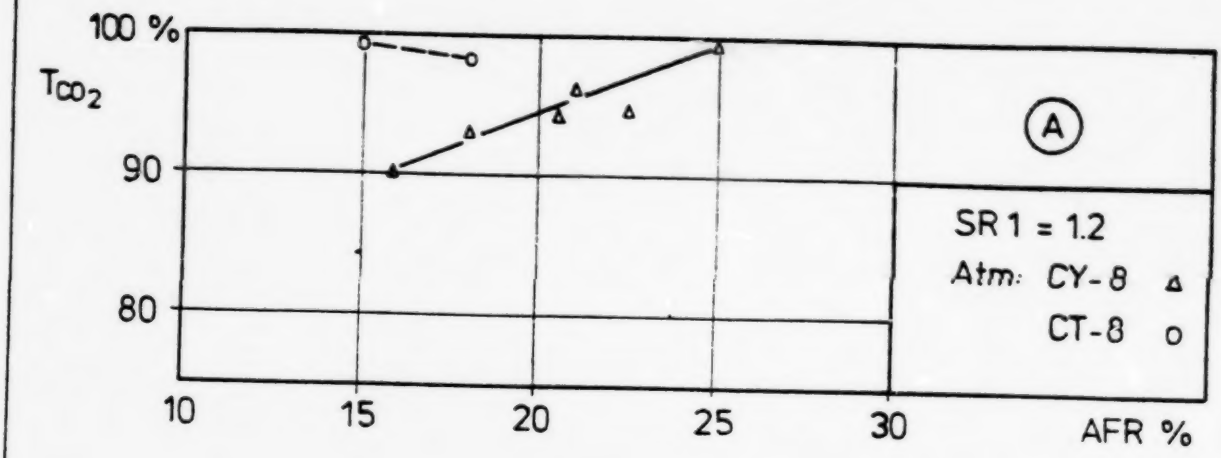
CWS - C , FC = 3/4 , S = 0.9

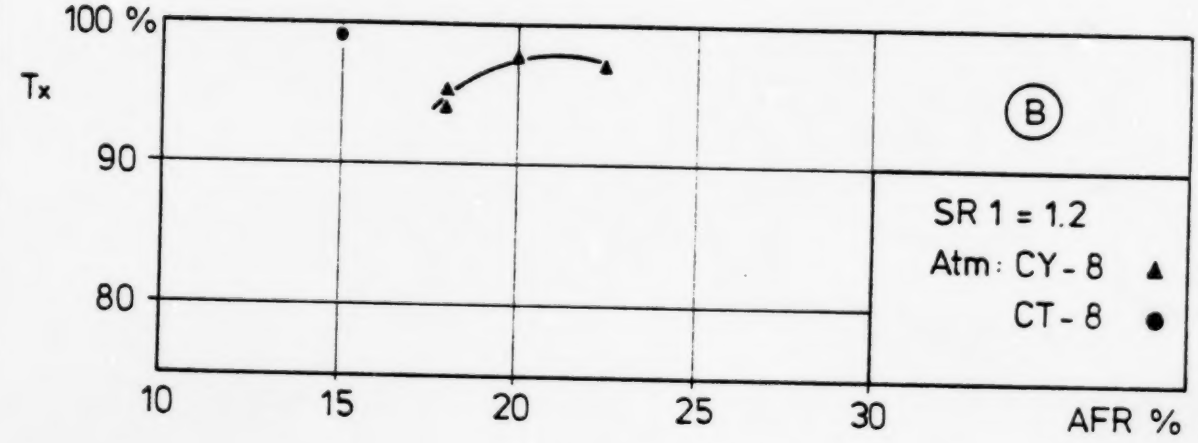


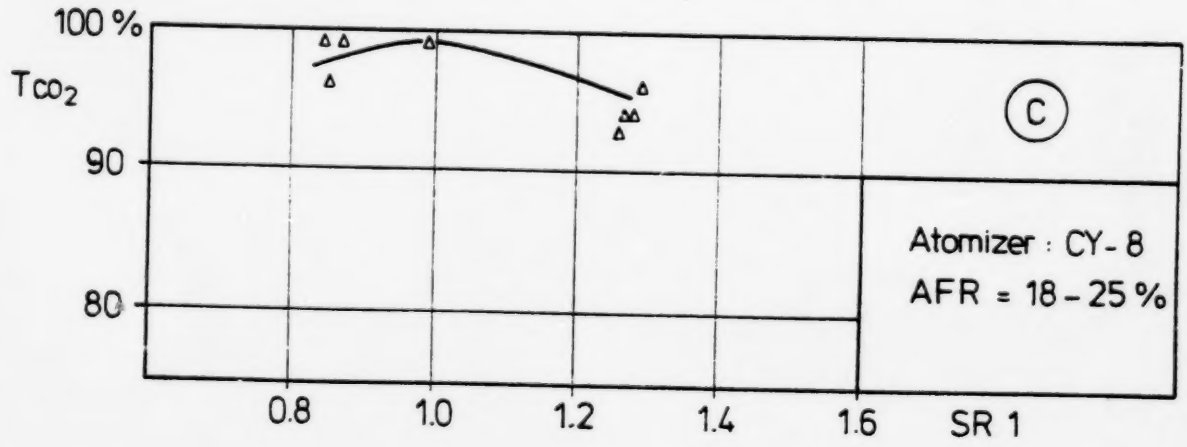
IFRF

Fig: 27 Isotherms for CWS - C

Tsec. = 300 °C



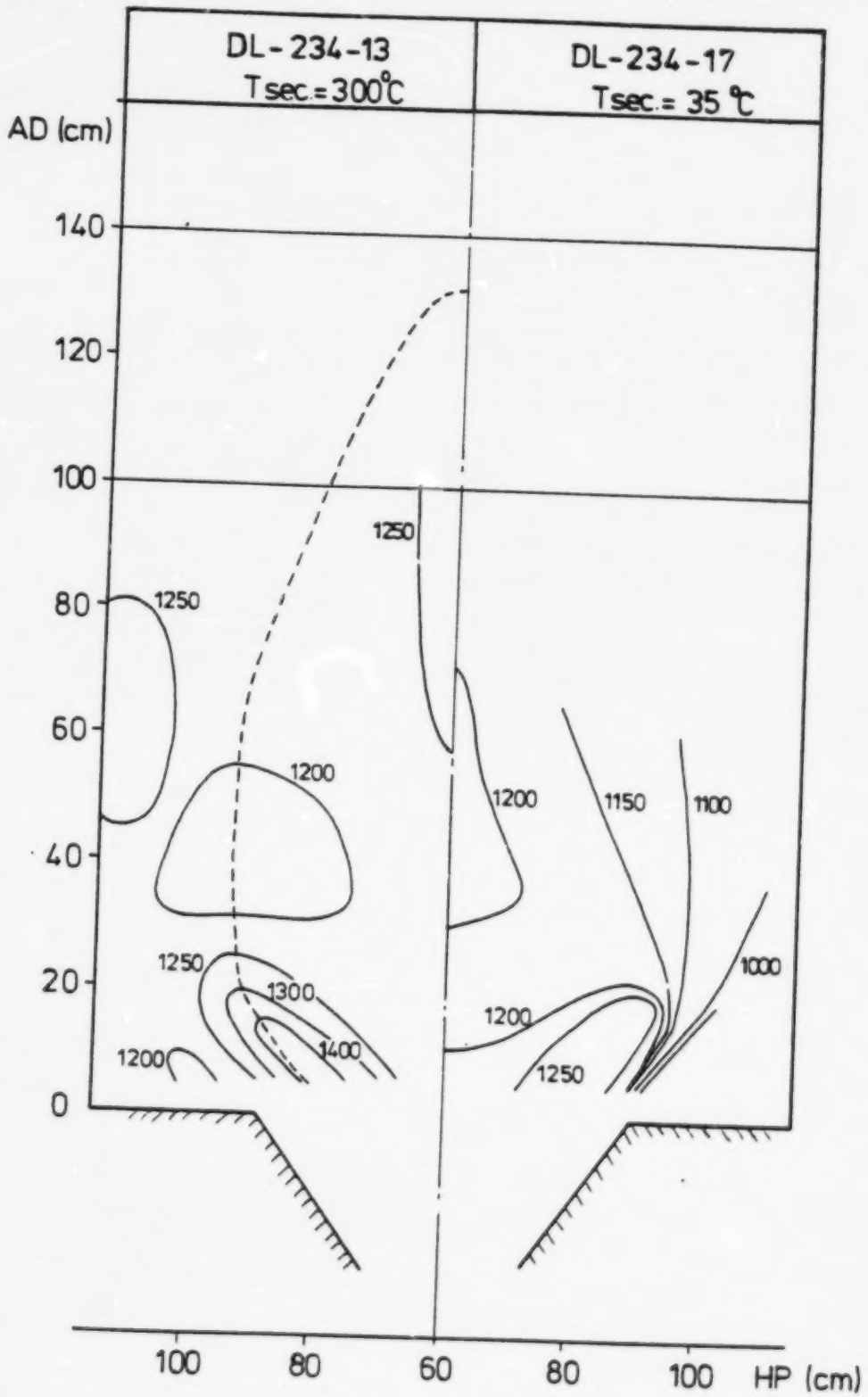




IFRF

Fig: 28 Burnout versus AFR and SR 1

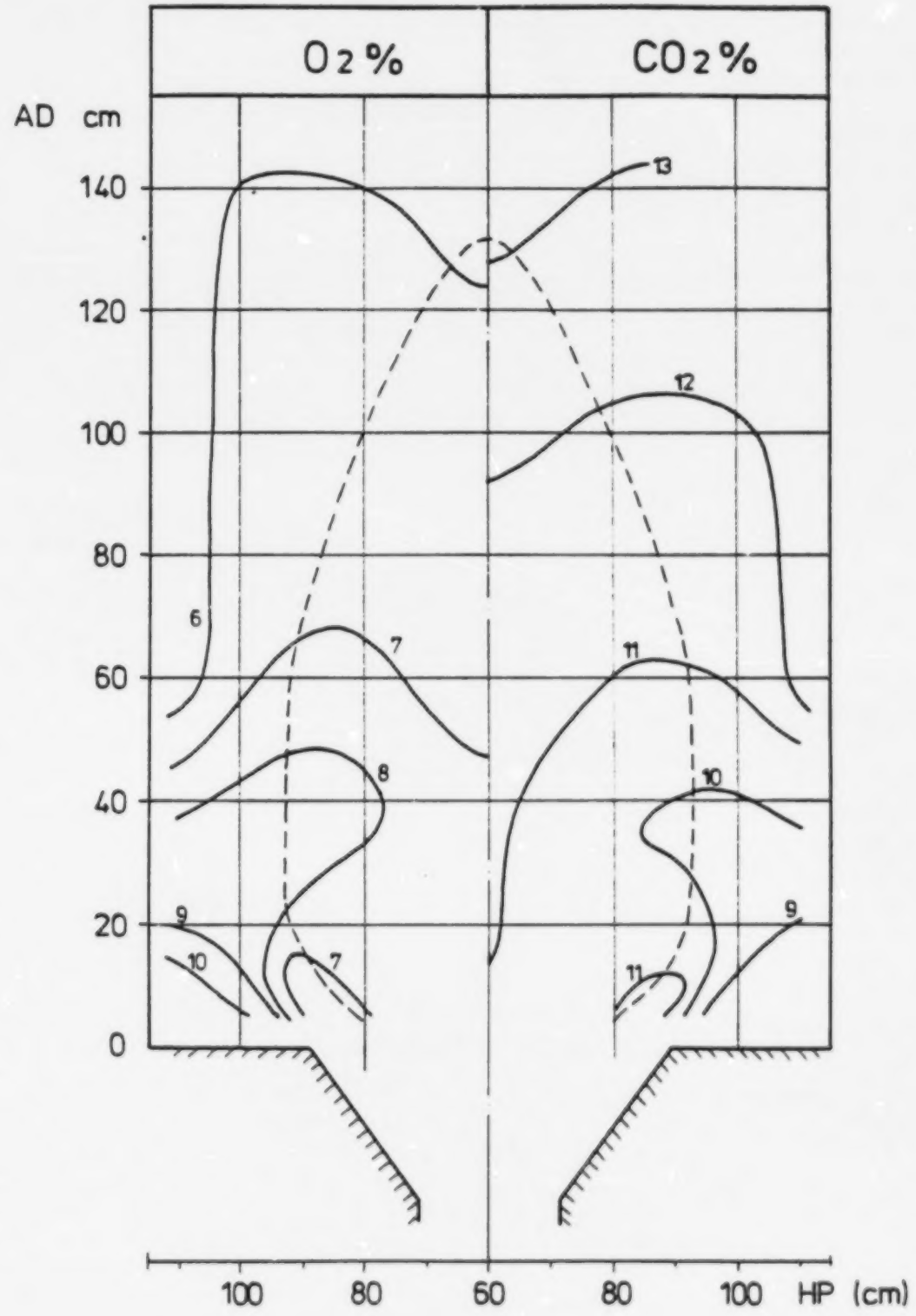
CWS - D , T_{sec} = 300 °C , S=0.9



IFRF

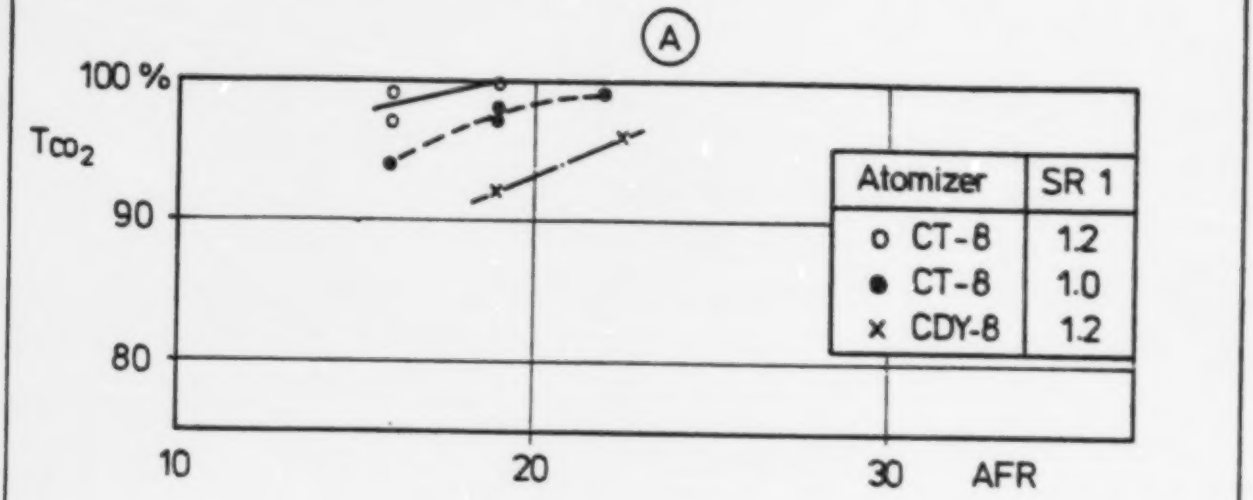
84-0013

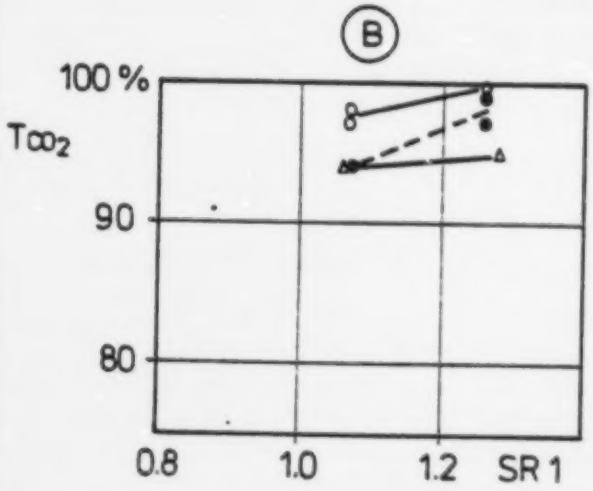
Fig:29 Isotherms for CWS-D baseline flames; Tsec. 300 °C, 35 °C

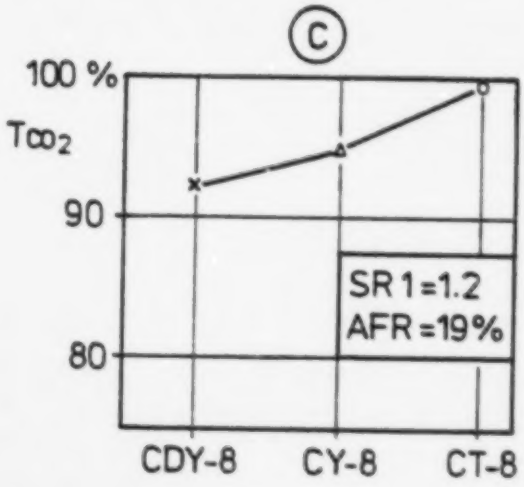


IFRF

Fig. 30 Isolines for O_2 and CO_2 flame DL-234-13



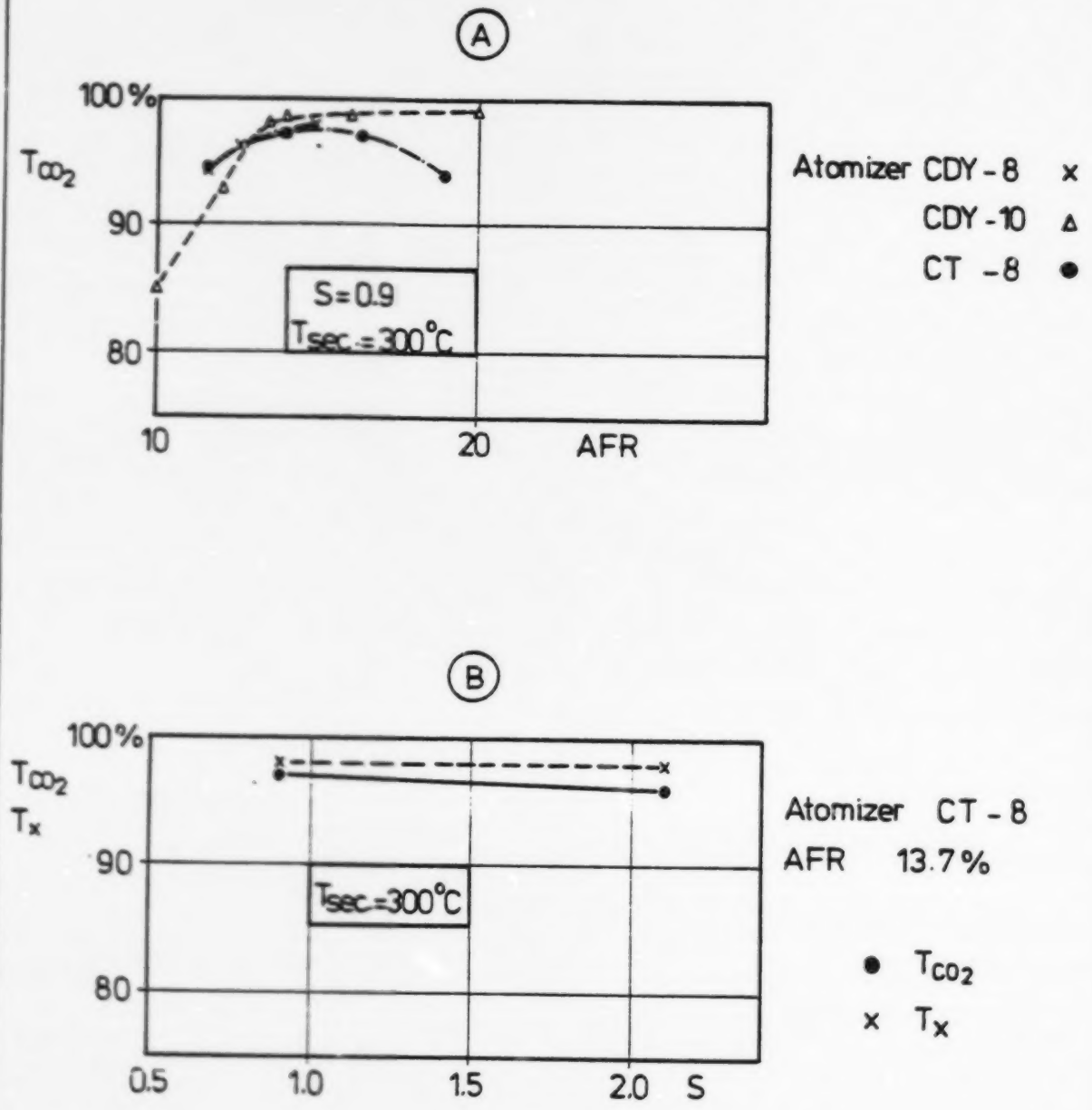




Atomizer	AFR
o CT-8	19
● CT-8	16
Δ CY-8	19
× CDY-8	19

IFRF

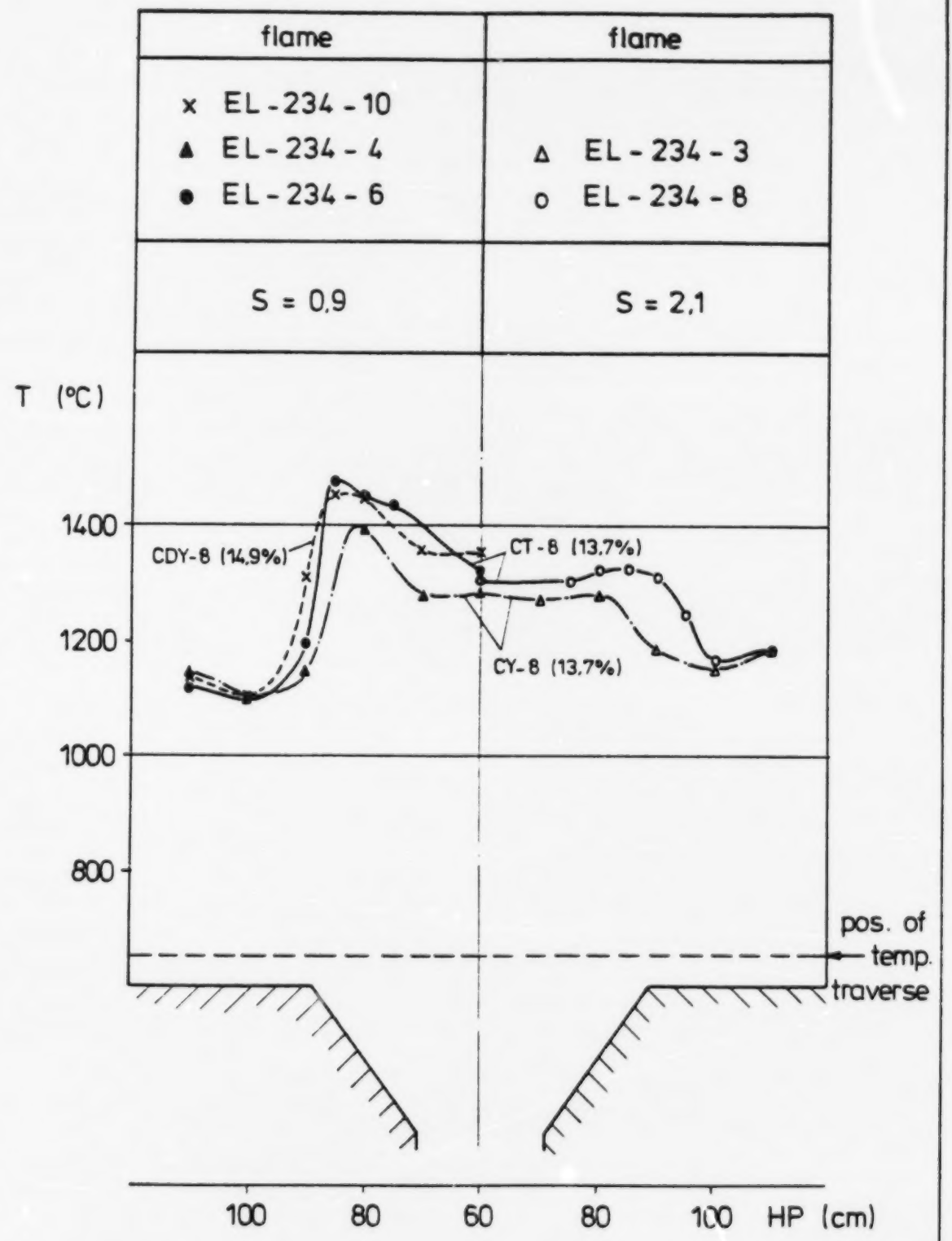
Fig. 31 Burnout versus AFR and SR 1
effect of atomizer type
CWS-D , $T_{sec.}$ = 30 °C , S = 2.1



IFRF

Fig. 32 Burnout versus AFR and swirl

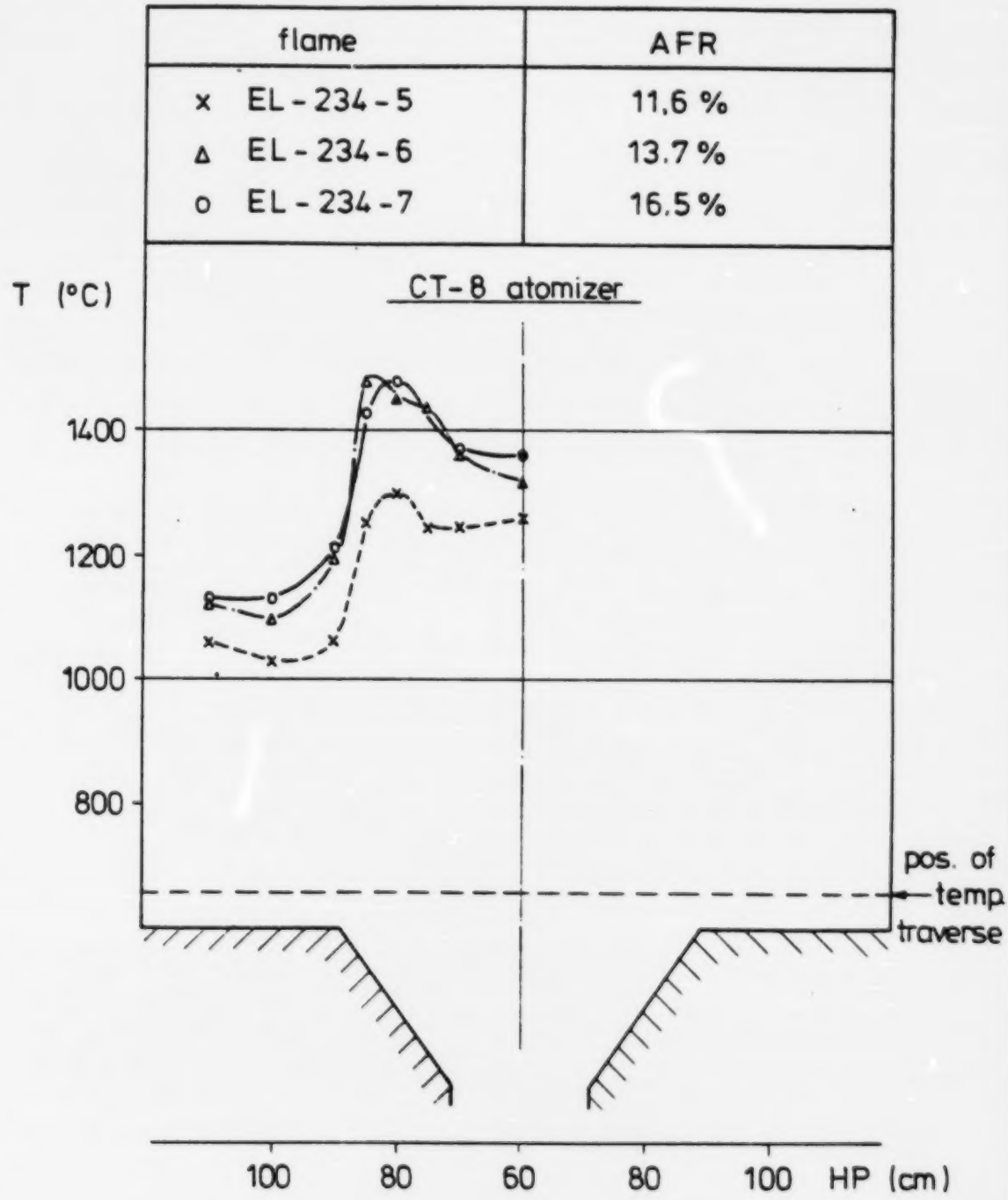
CWS - E , SR 1=1.2



IFRF

84-0015

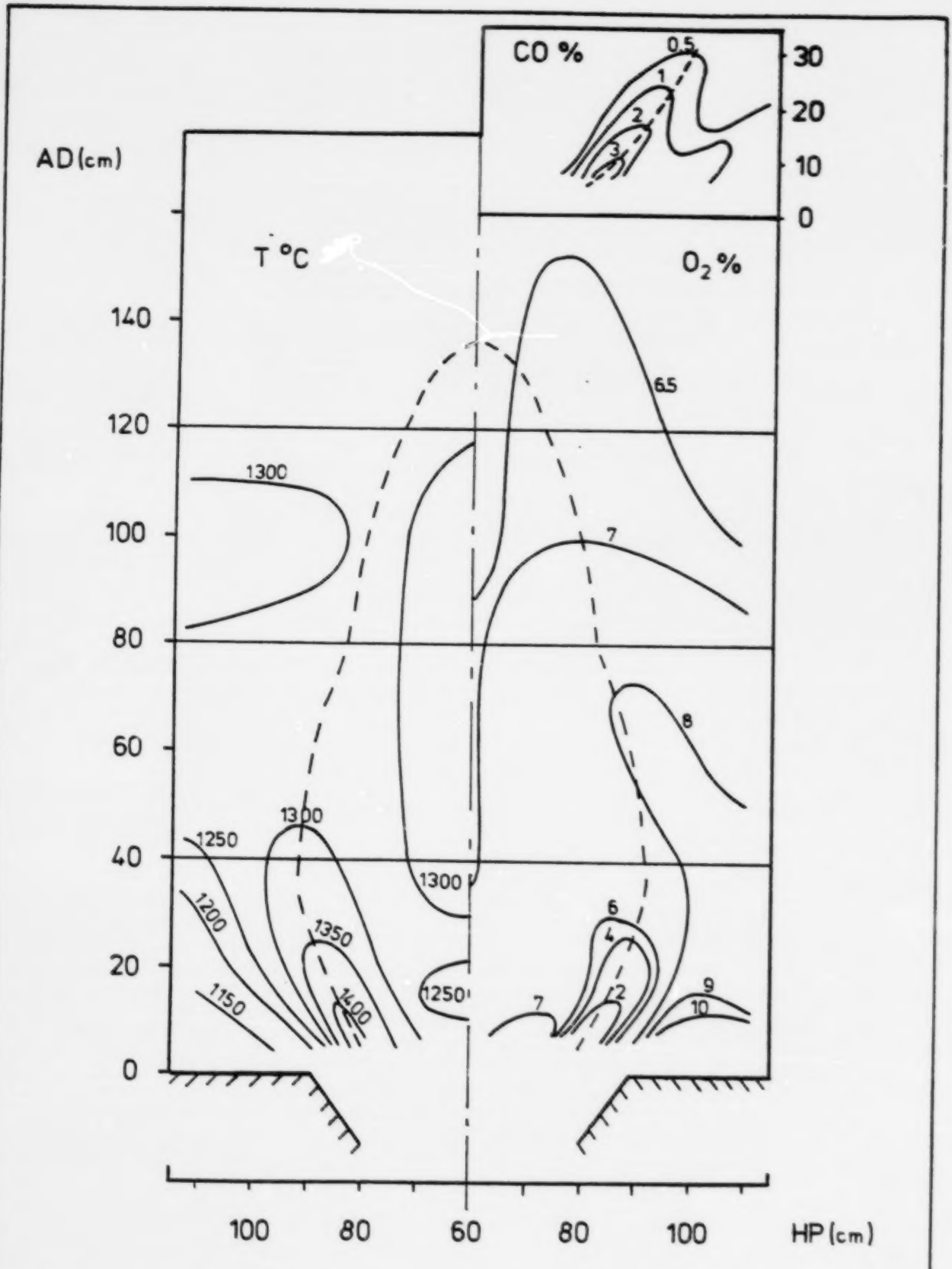
Fig: 33 Radial temperature profiles at AD 8
effect of atomizer-type (AFR)
CWS-E ; SR 1 = 1,2



IFRF

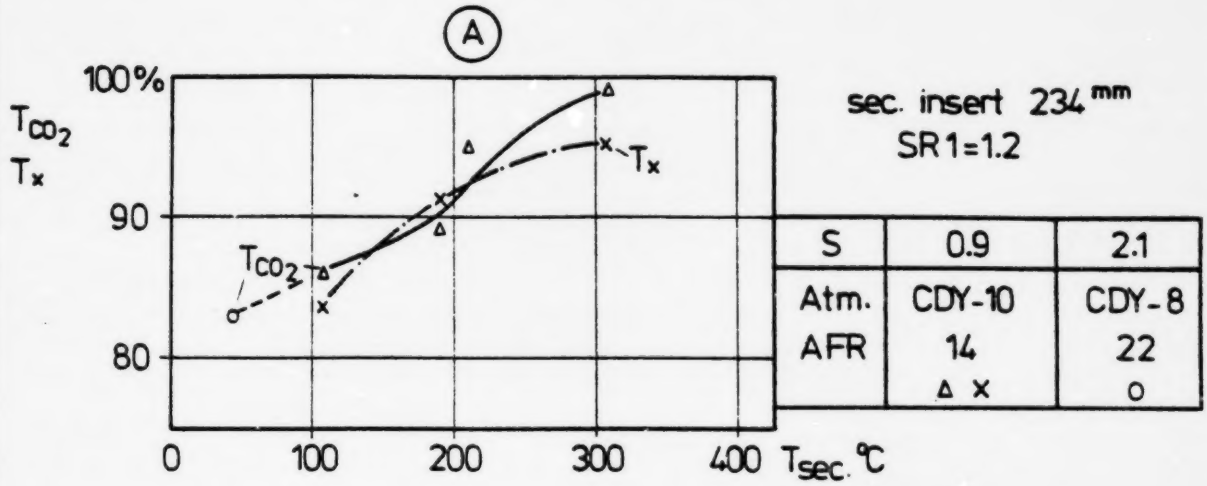
84-0017

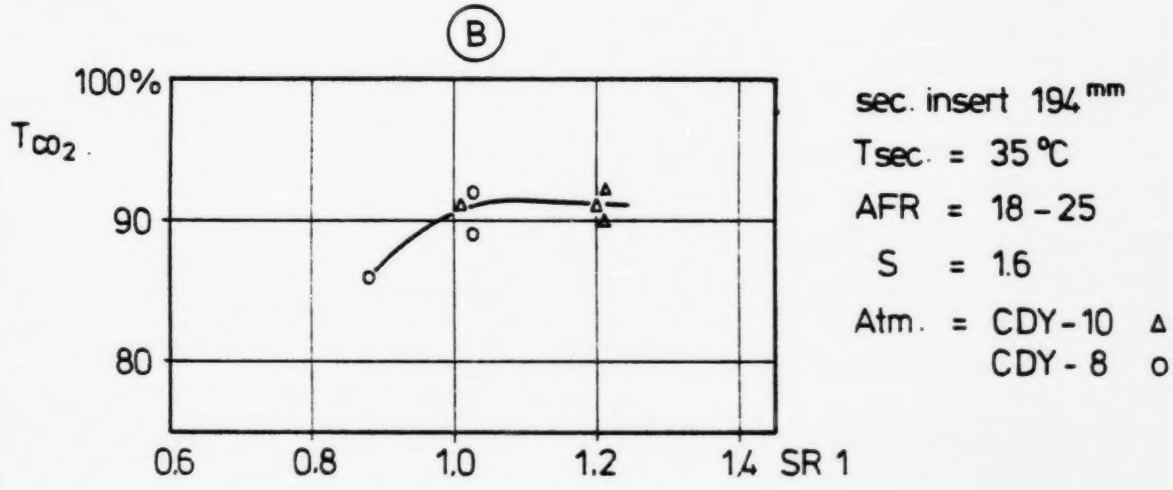
Fig: 34 Radial temperature profiles at AD 8
effect of atomizing air rate
CWS-E ; SR 1 = 1,2 S = 0.9



IFRF

Fig: 35 In-flame measurements for flame EL - 234 - 13

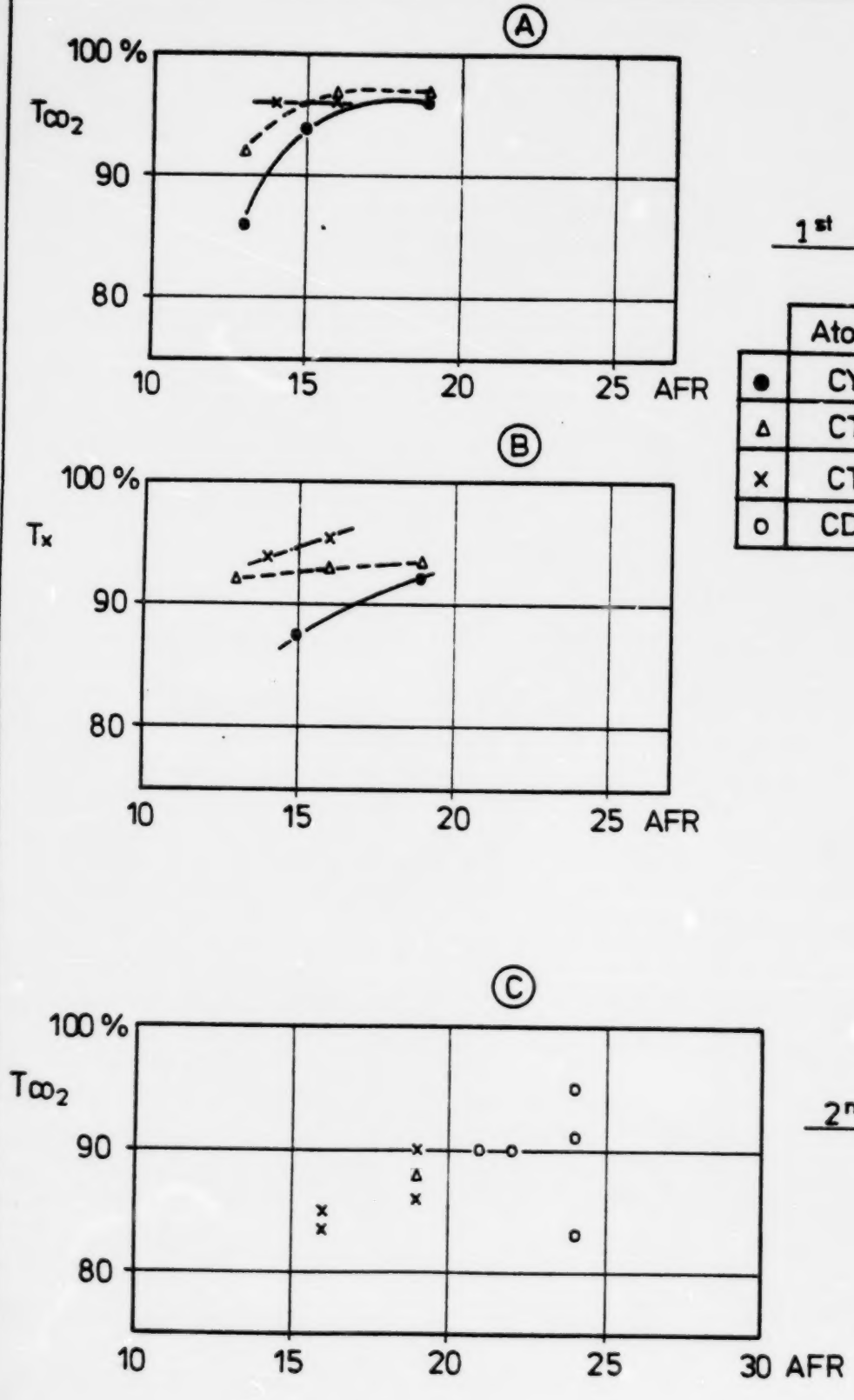




IFRF

Fig: 36 Burnout versus $T_{sec.}$ and SR 1

CWS - E

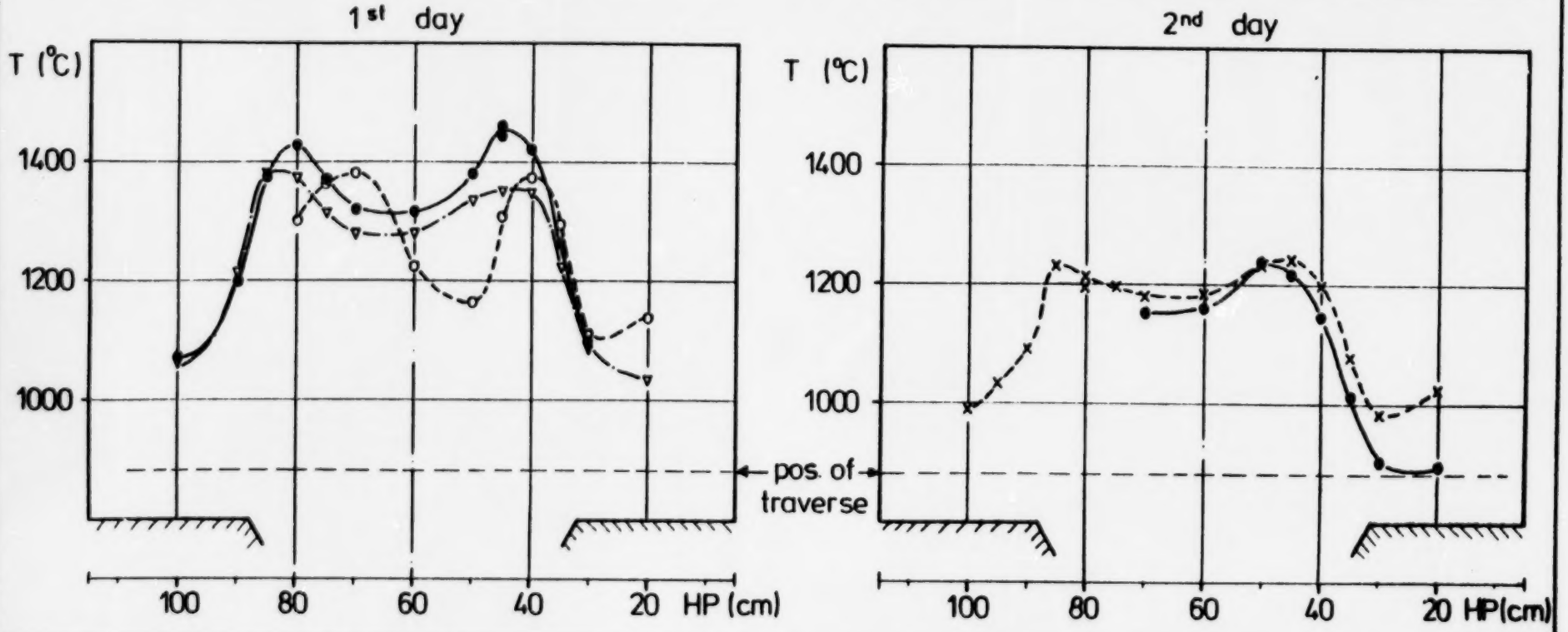


IFRF

Fig: 37 Burnout as a function of AFR
effect of time
CWS-F, FC = ¾, S = 0.9

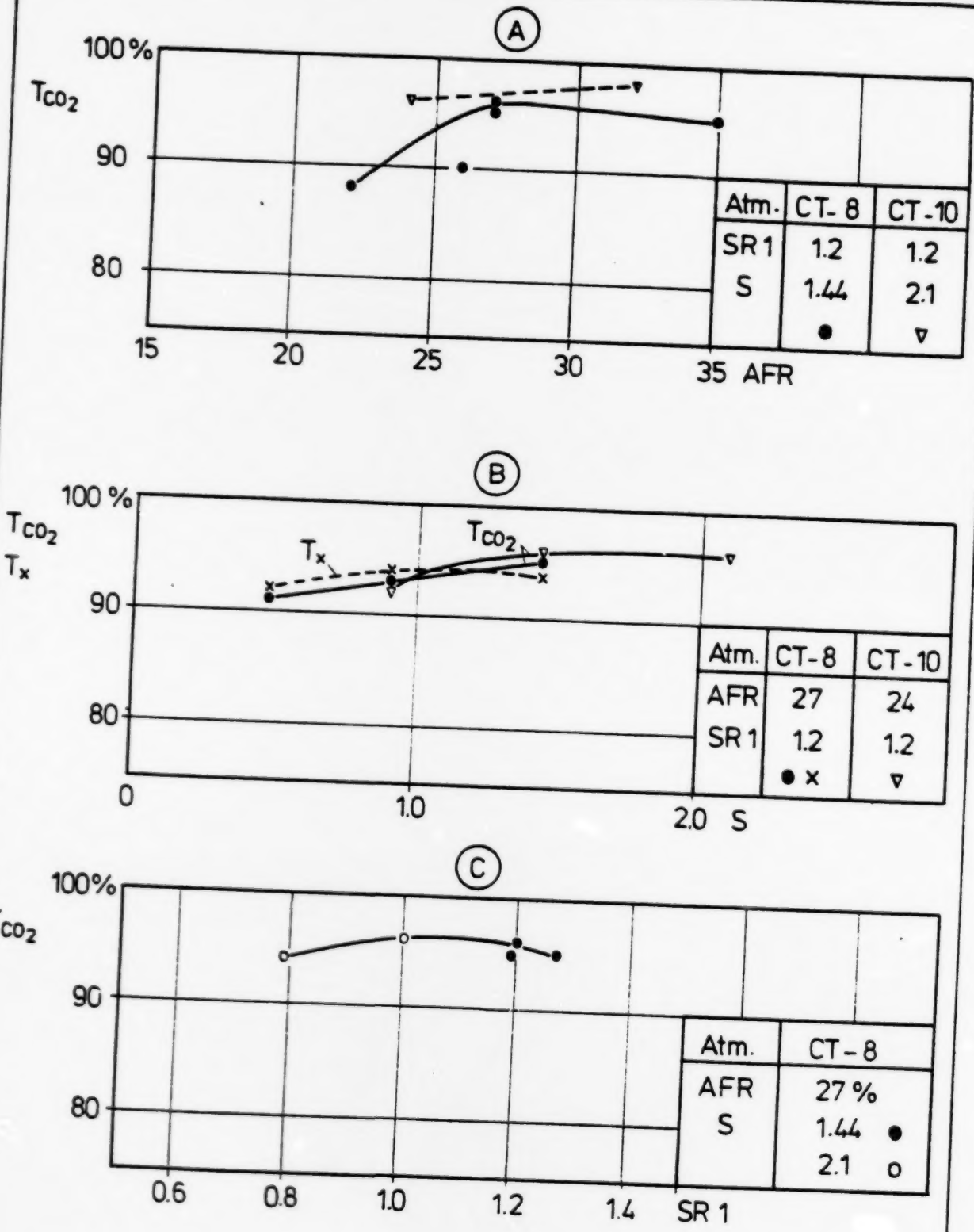
flame		atomizer	AFR (%)
·—▽—·	FL-234-8	CY-6	15
---o---	FL-234-9	CY-10	15.5
—●—	FL-234-4	CT-8	16

flame		atomizer	AFR (%)
---x---	FL-234-15	CDY-8	24
—●—	FL-234-13	CT-8	19



IFRF

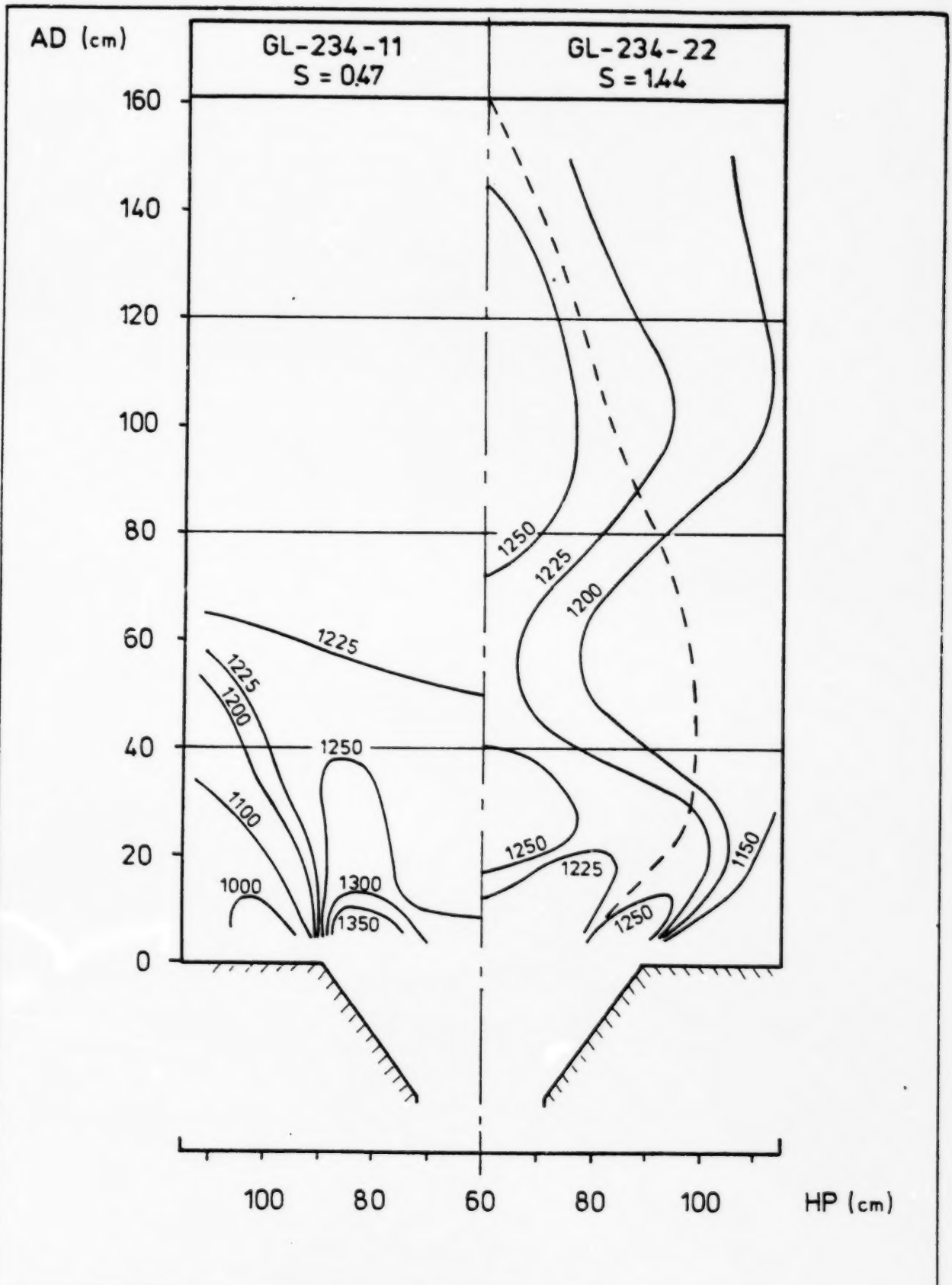
Fig: 38 Radial temperature profiles at AD 8
effect of atomizer type CWS-F, SR 1=12, S=0.9



IFRF

Fig: 39 Burnout versus AFR, swirl and SR 1

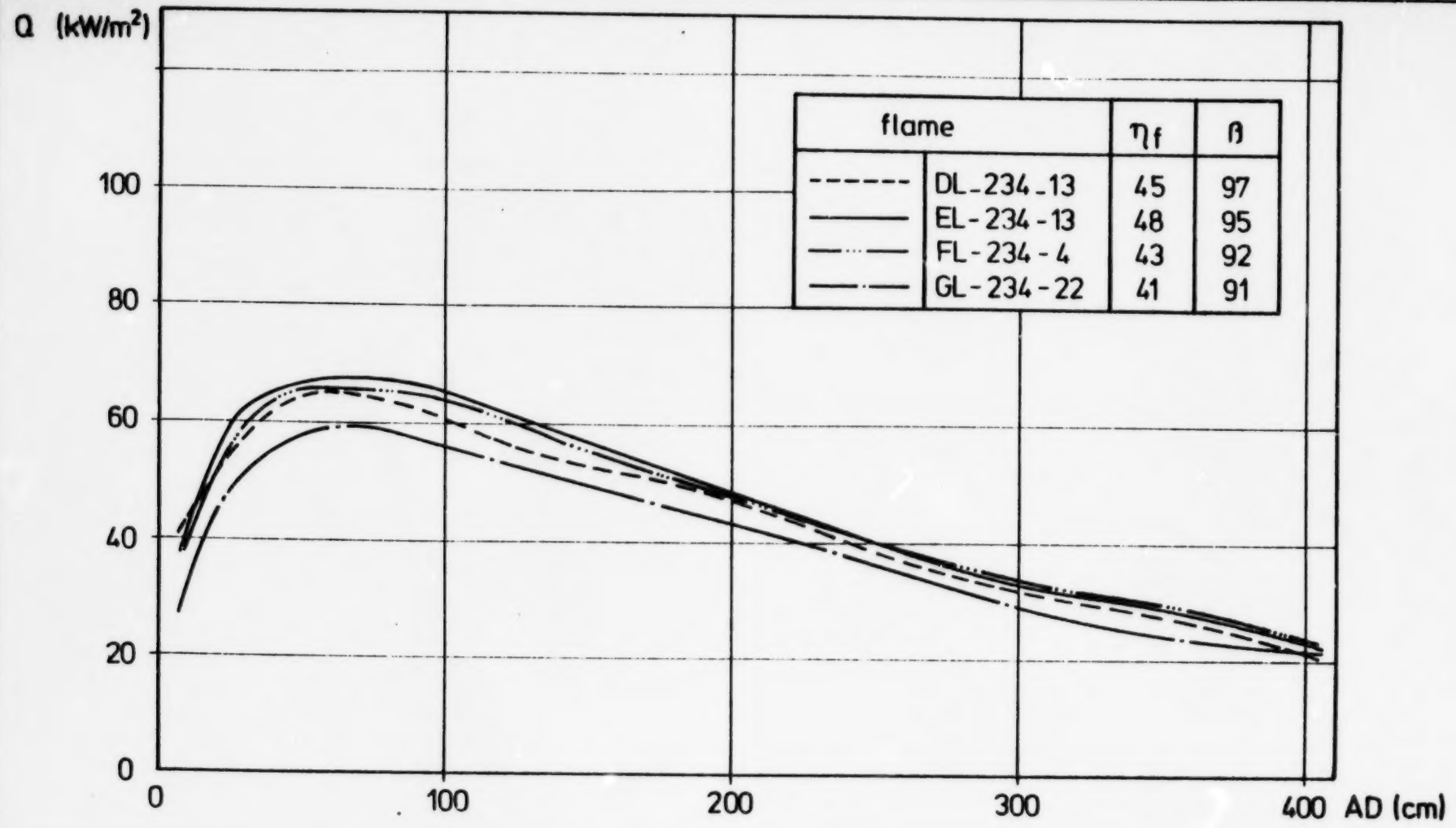
CWS - G, $T_{sec.}$ = 300 °C



IFRF

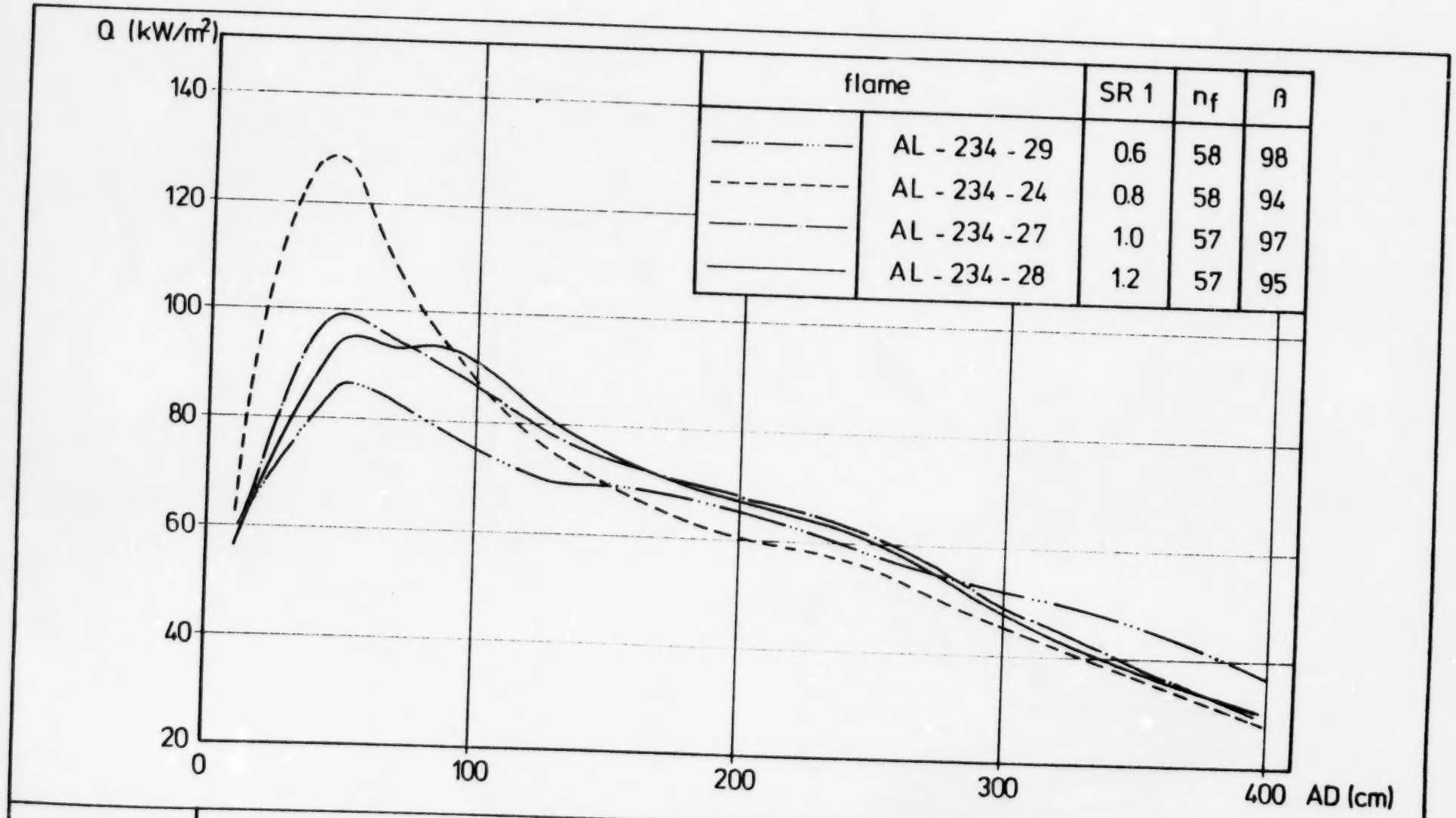
Fig: 40 .Isotherms : effect of swirl

CWS - G , SR 1=1.2 , Tsec. 300 °C



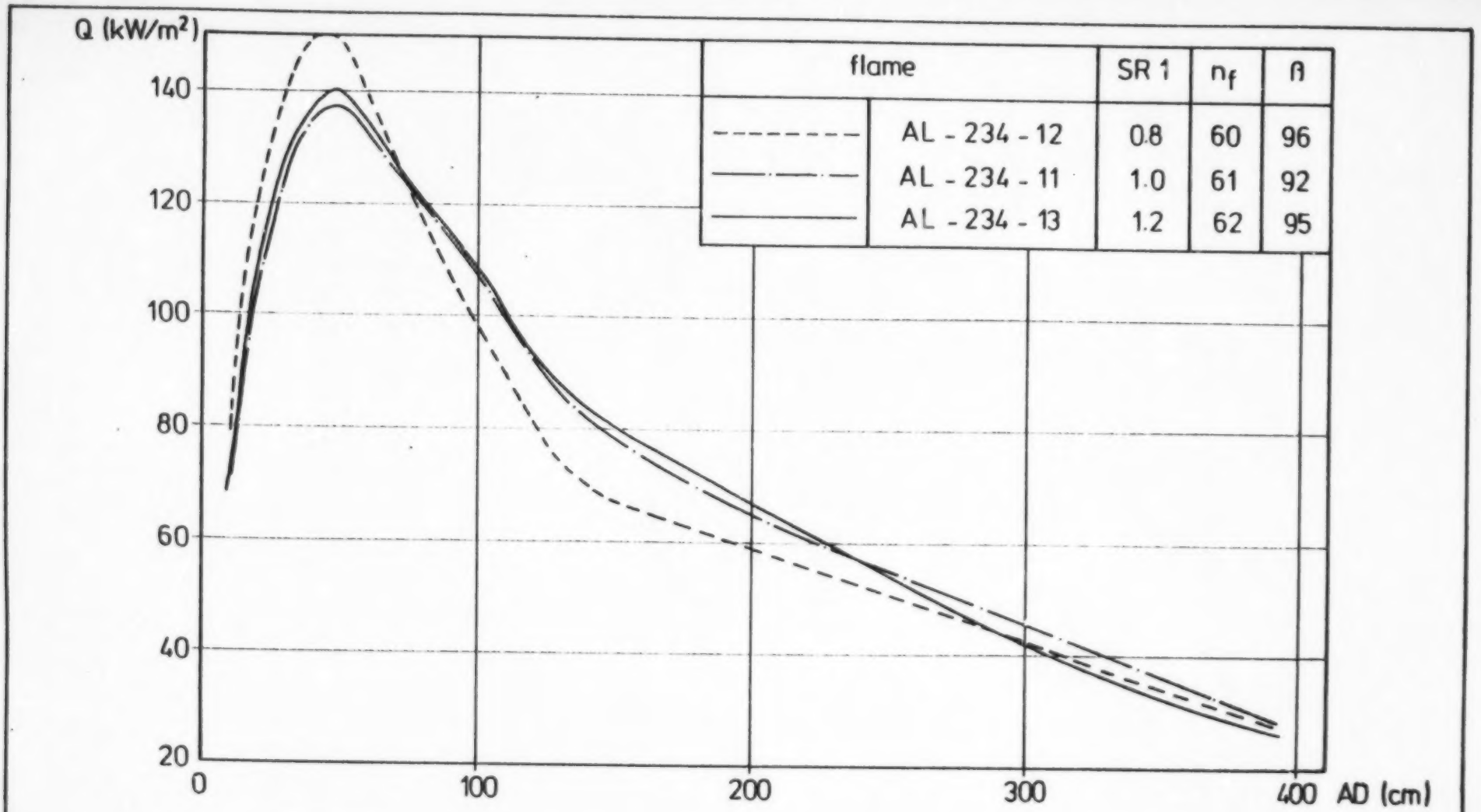
IFRF

Fig. 41 Heat flux profiles for high volatile coal slurries
FC = ¾ , SR 1 = 1.2



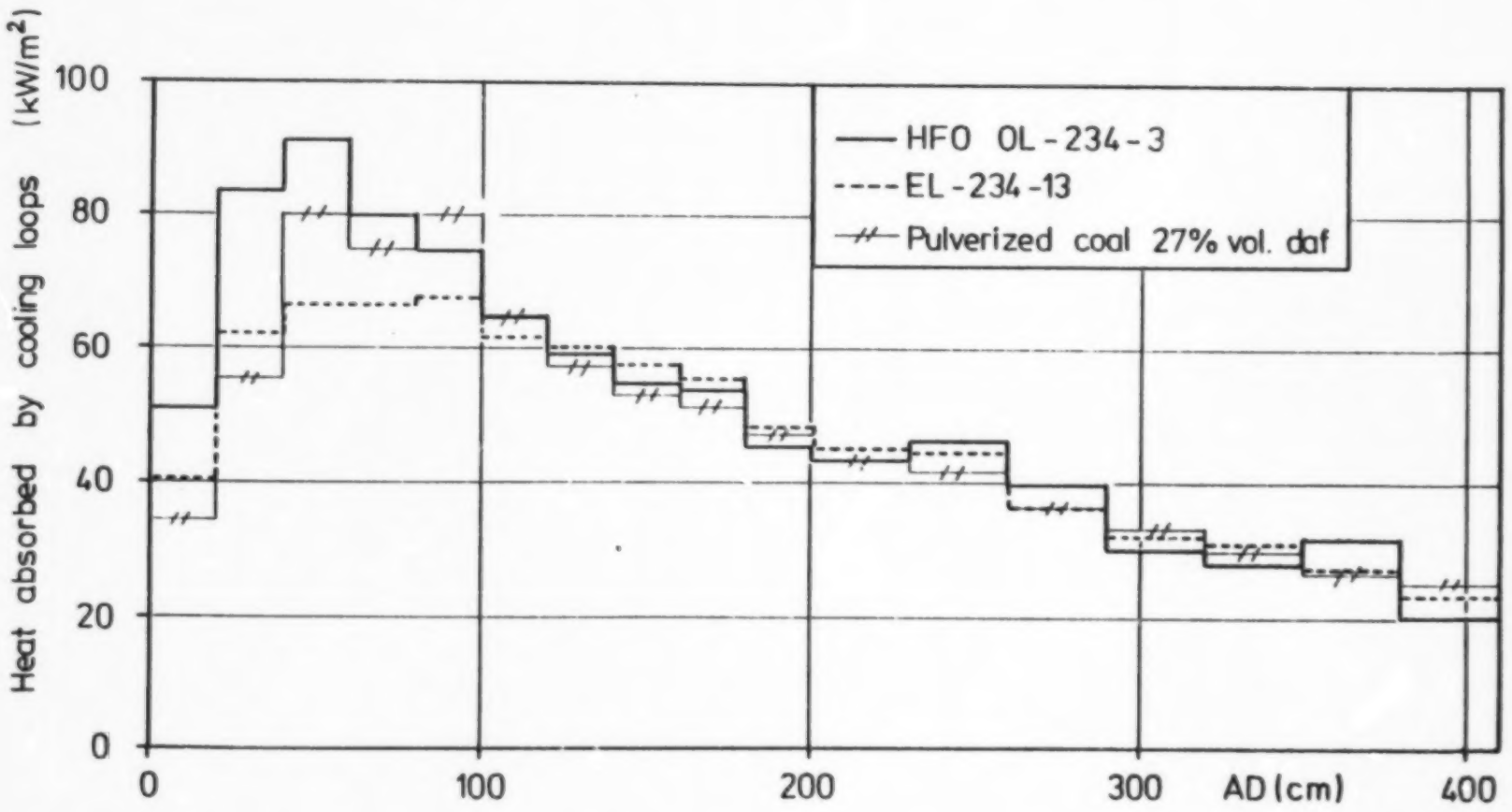
IFRF

Fig: 42 · Heat flux profiles ; effect of staging
CWS - A , S = 2.1 , FC = 1/4



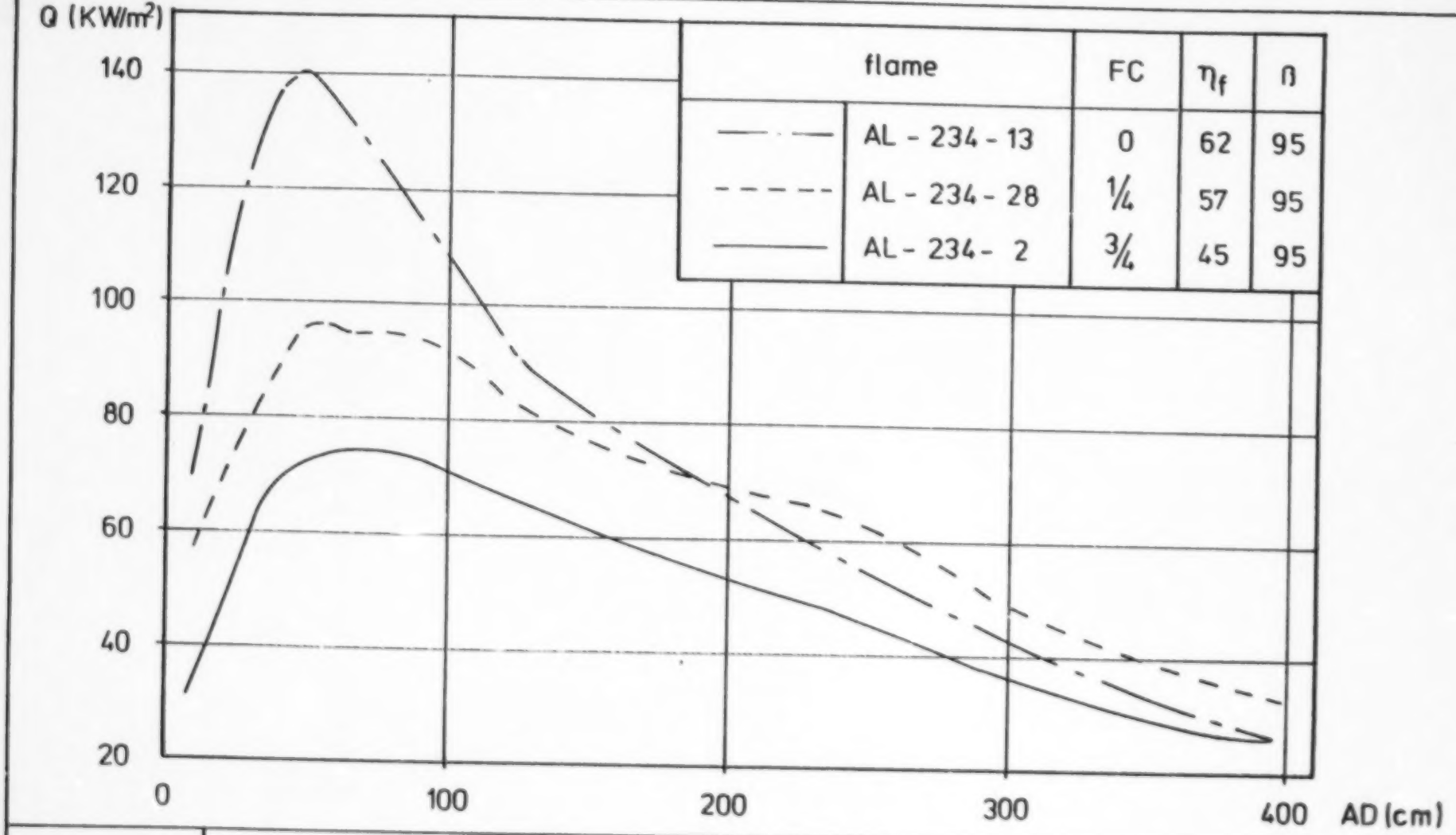
IFRF

Fig: 43. Heat flux profiles : effect of staging.
CWS - A , S = 0.9 , FC = 0



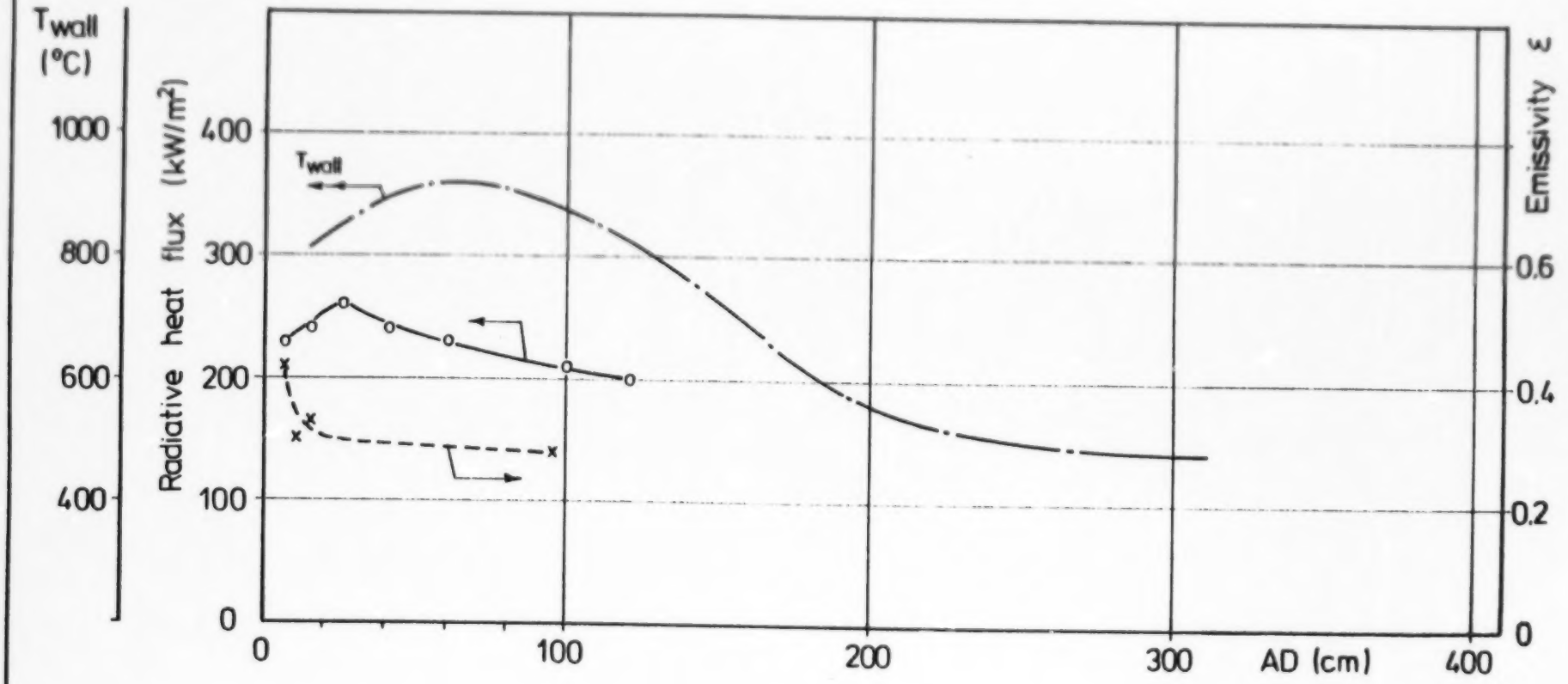
IFRF
84-C005

Fig: 44 Heat flux profiles for the baseline CWS and HFO flame, T_A = 300 °C, furnace insulation 3/4



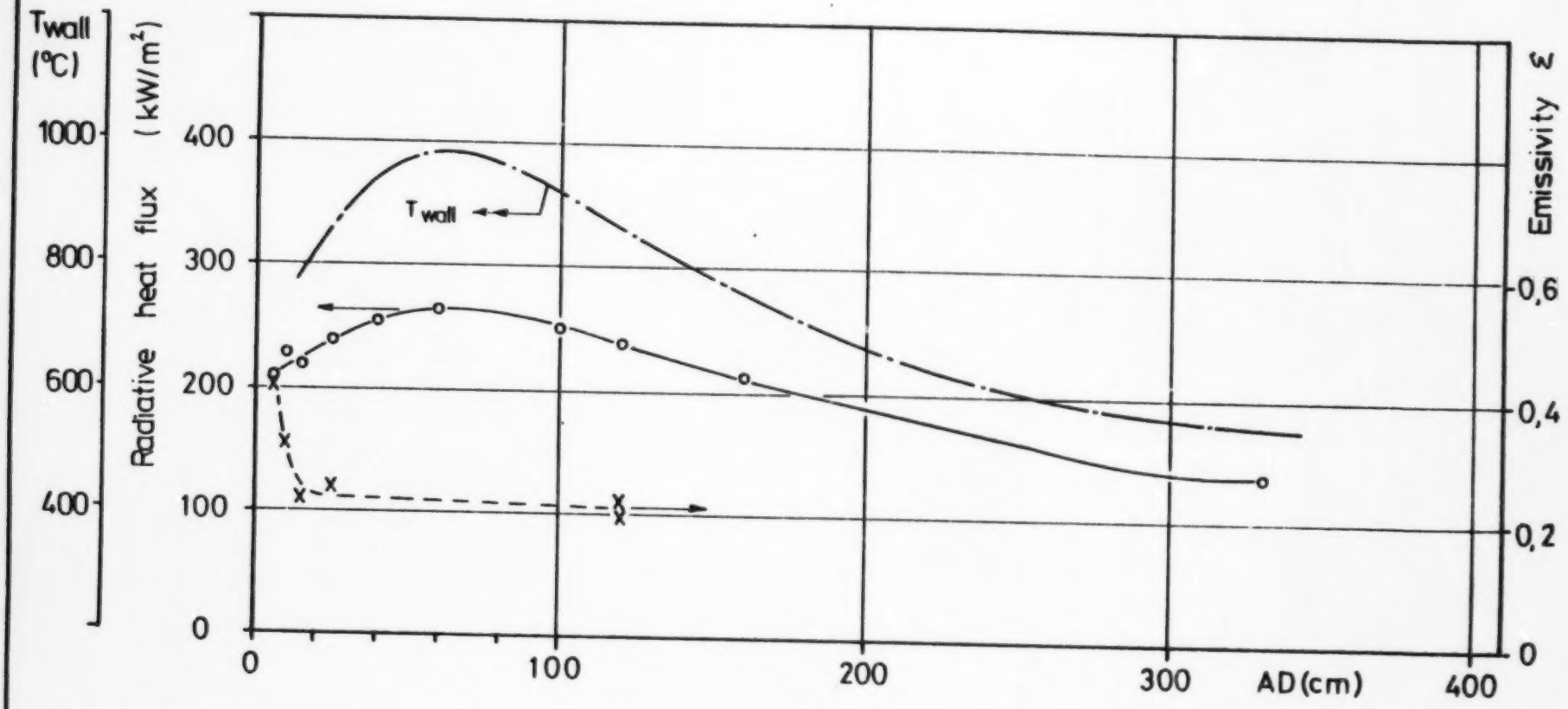
IFRF

Fig: 45 .Heat flux profiles ; effect of furnace lining.
CWS - A , SR 1 = 1.2



IFRF

Fig: 46 Radiative heat flux and emissivity
CWS - D , flame (DL - 234 -13)



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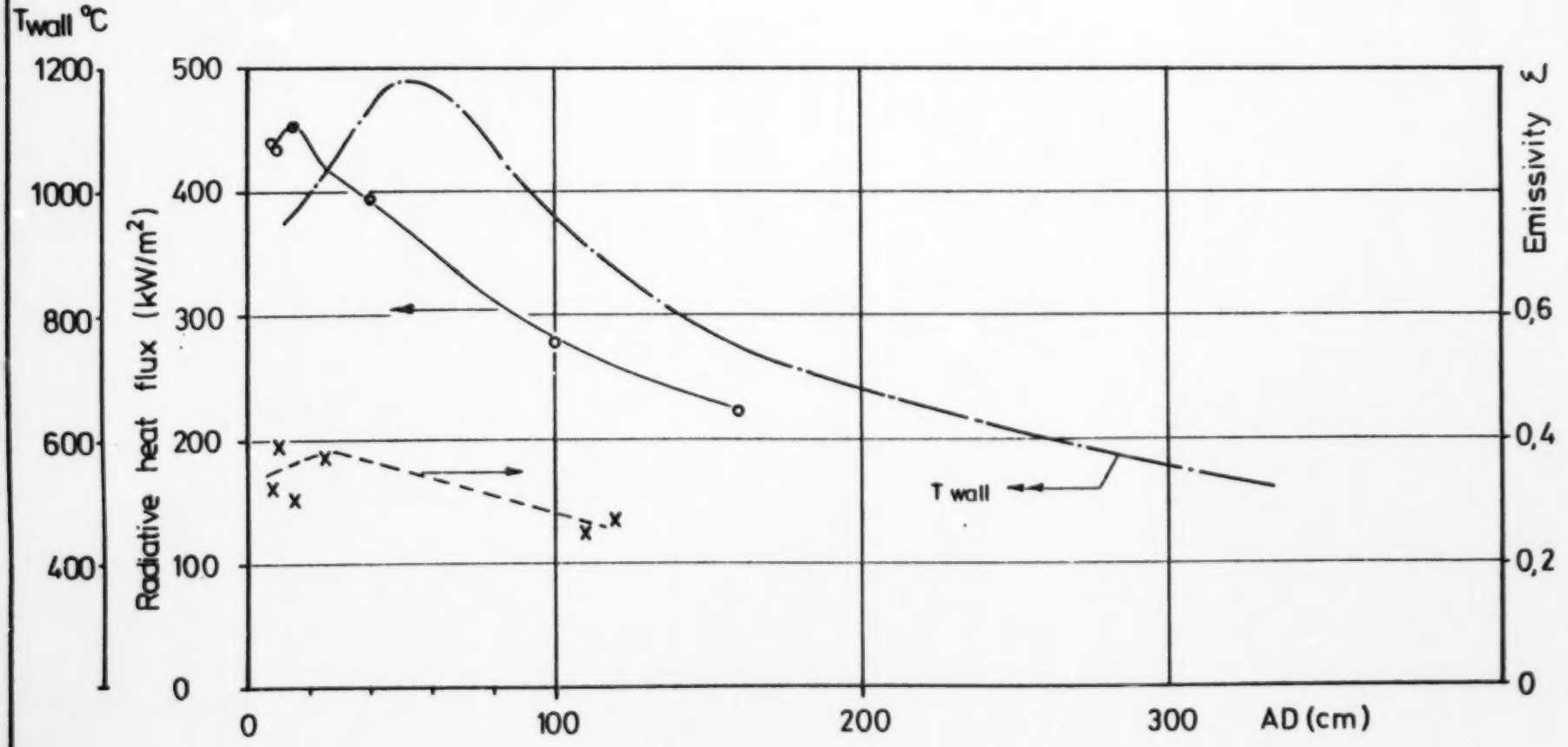
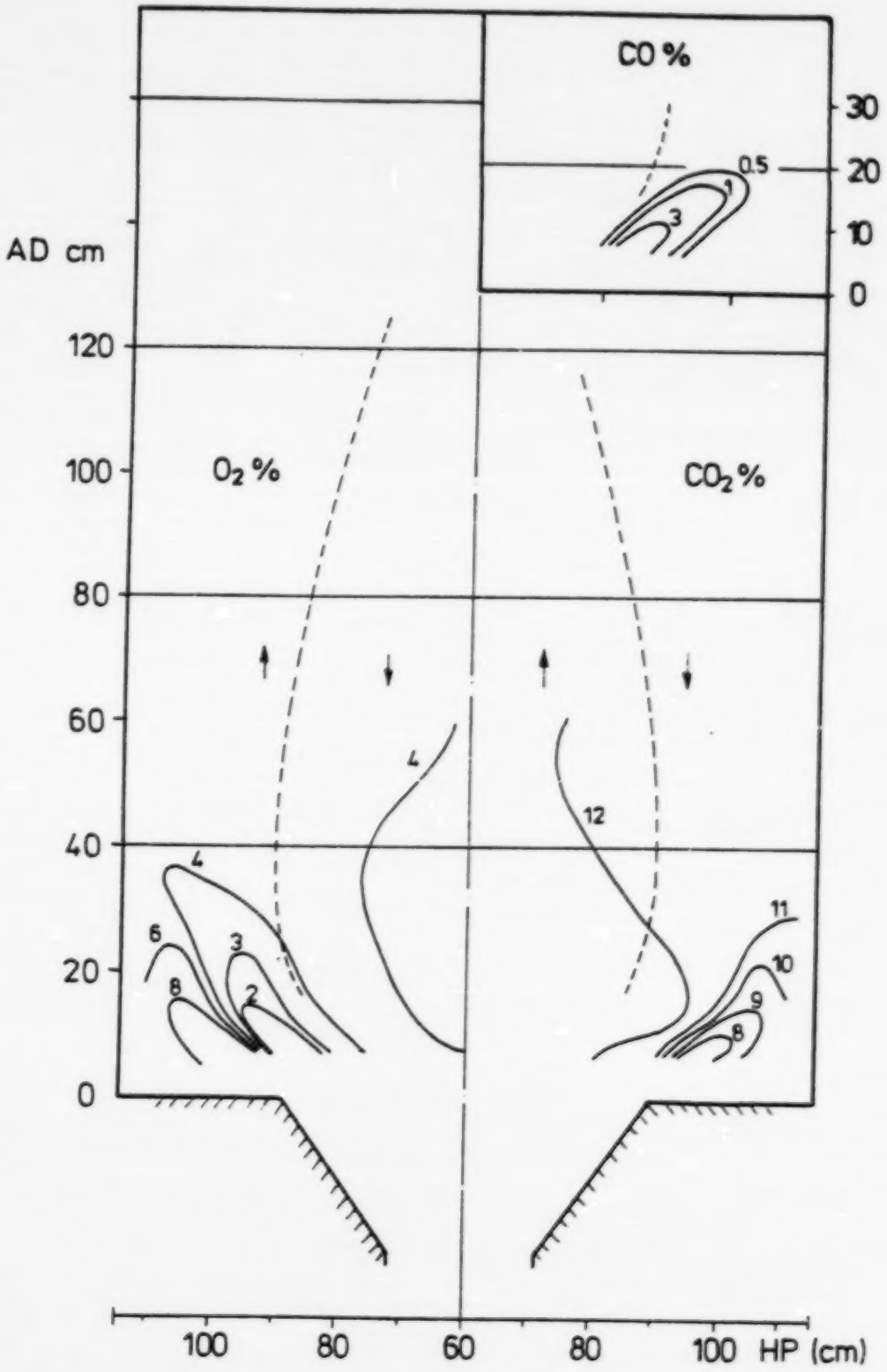
84-0004

Fig:47. Radiative heat flux and emissivity for the baseline CWS - E flame (EL - 234 - 13)



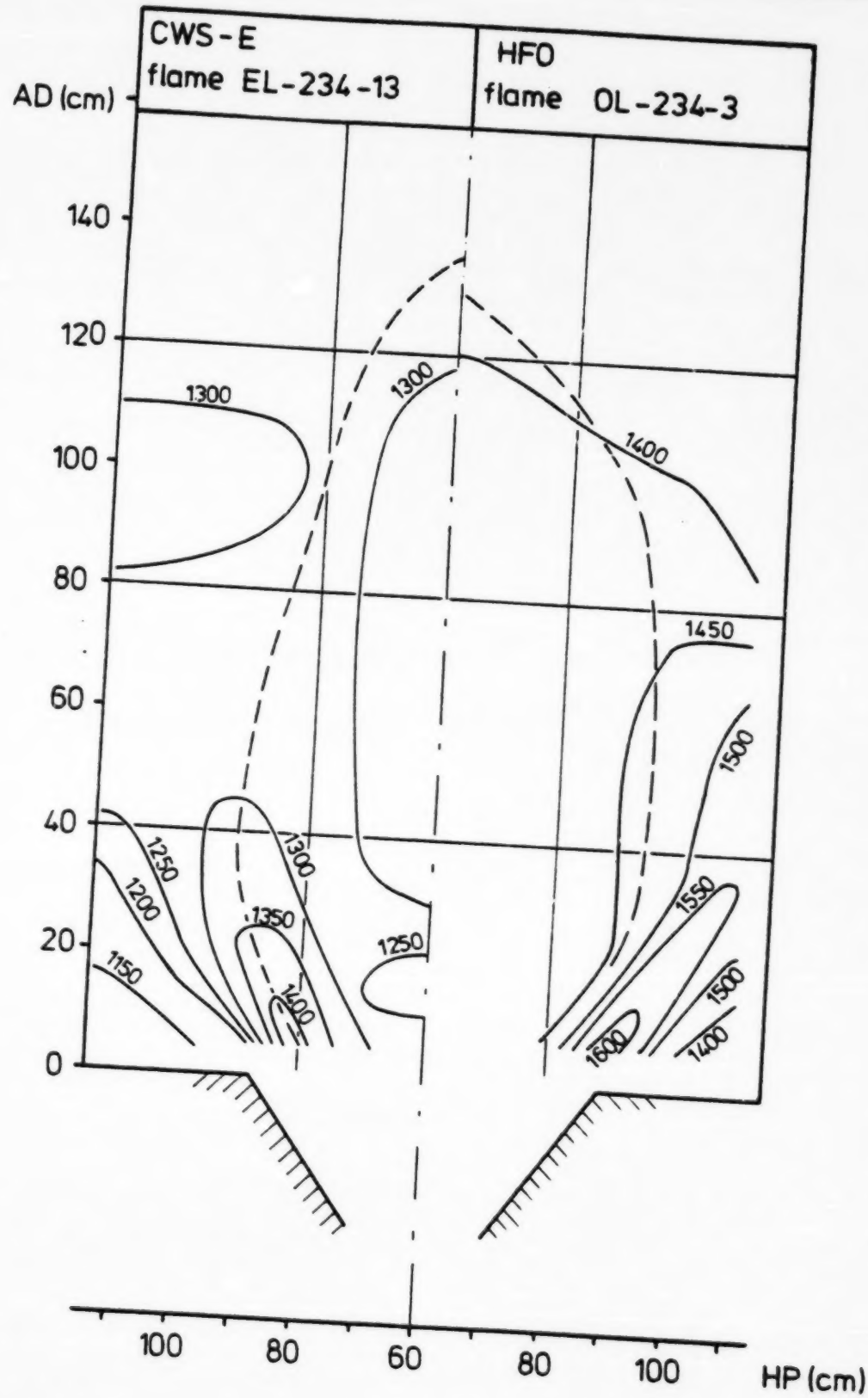
IFRF
84-0003

Fig:48. Radiative heat flux and emissivity for the baseline HFO flame (OL-234-3)



IFRF

Fig: 49 In-flame measurements for HFO flame OL-234-3



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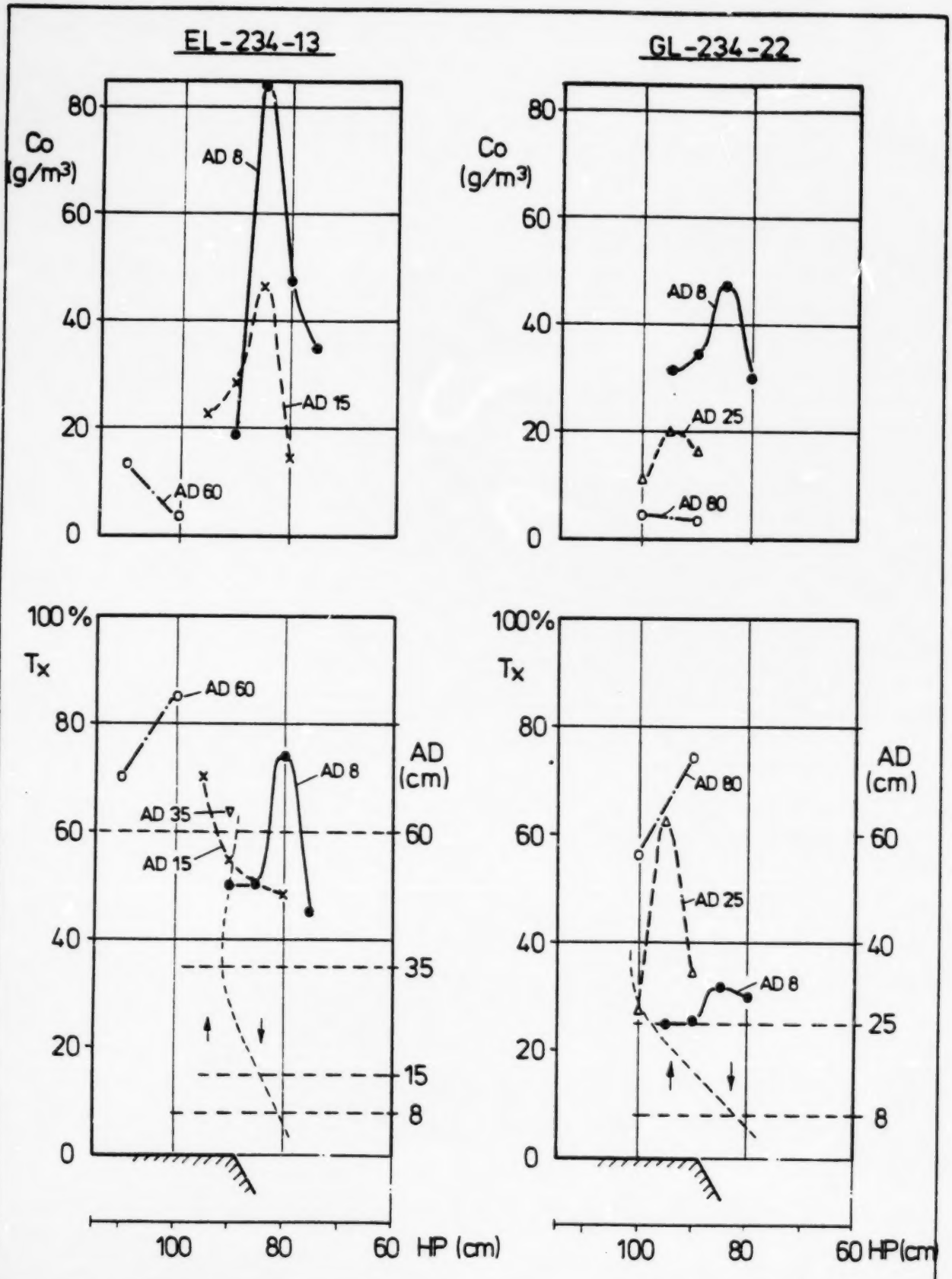
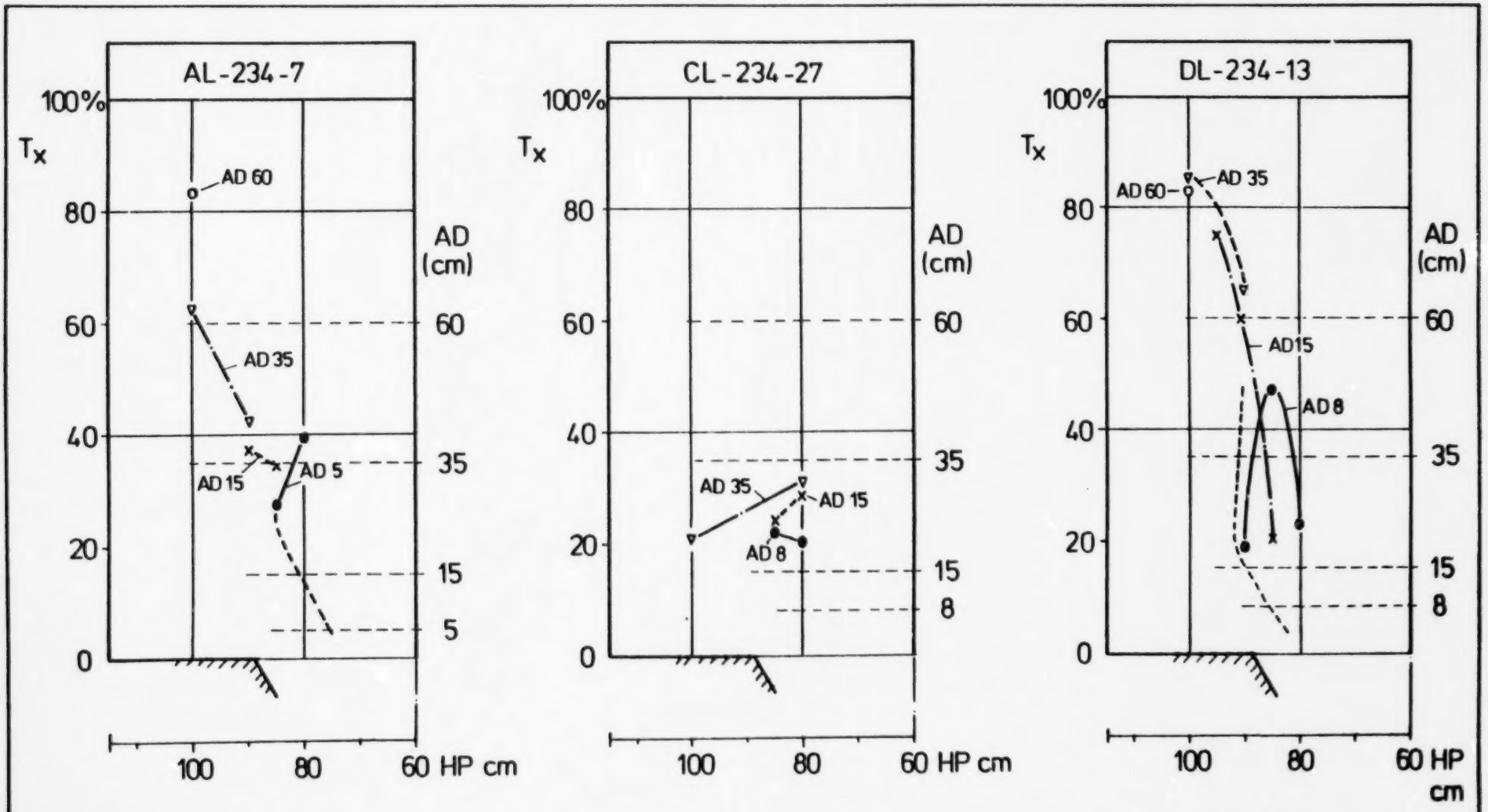
84-0002

Fig: 50 . Isotherms for the baseline CWS-E and HFO flame



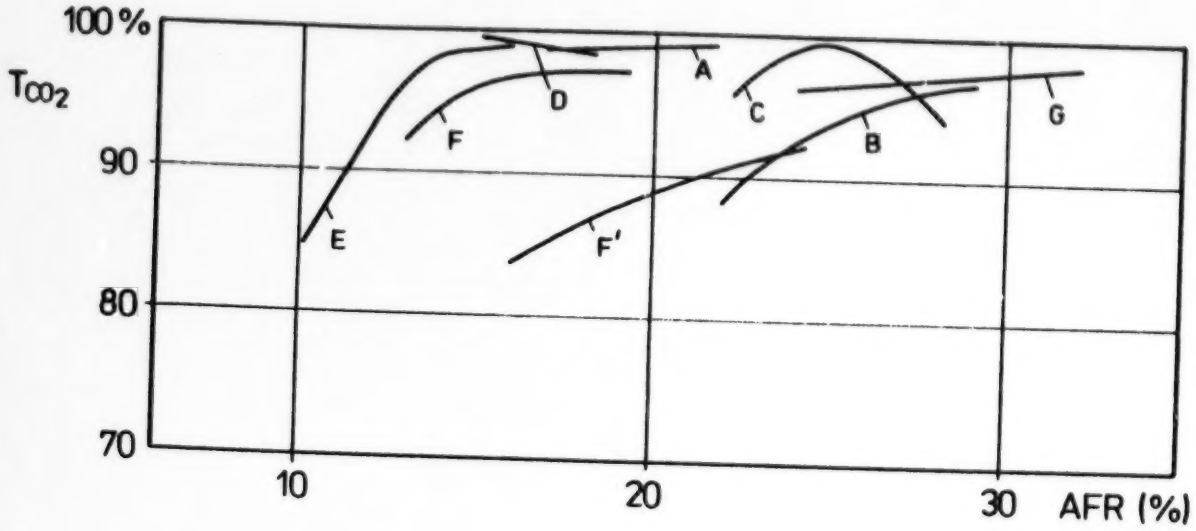
IFRF

Fig: 51 In-flame solid concentration and burnout CWS-E, G



IFRF

Fig: 52 Burnout of in-flame solid samples CWS - A.C.D



slurry type

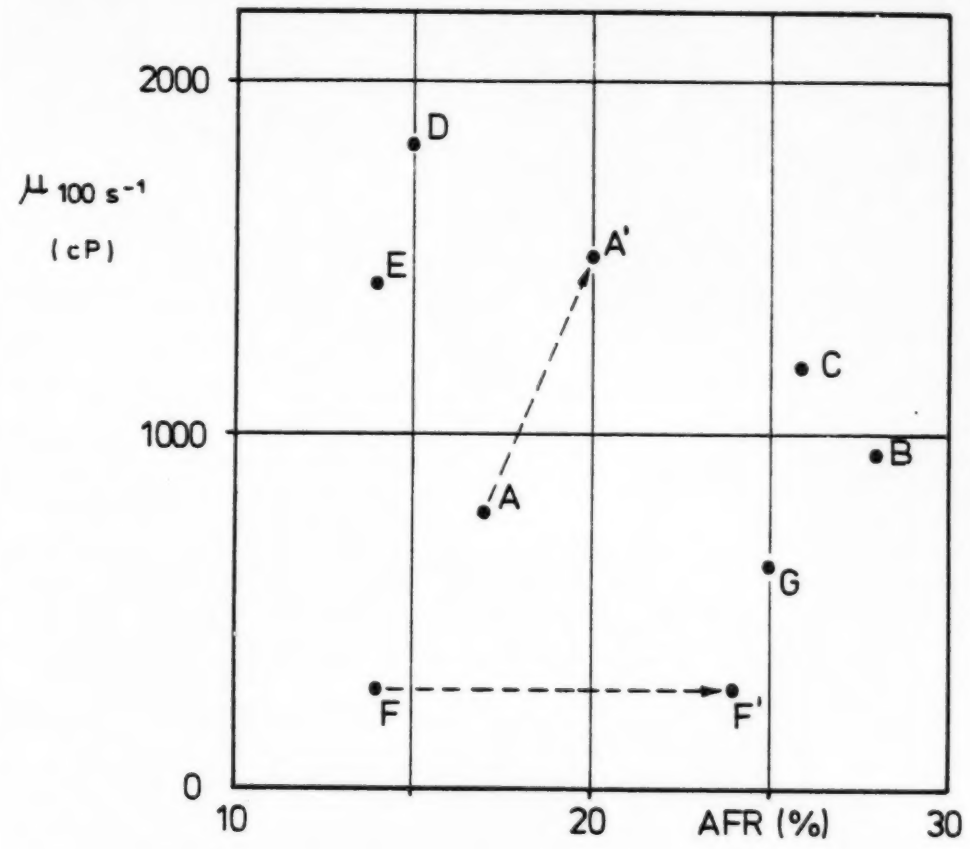
A - mvb
B - lvb
C - hvb
D - hvb
E - hvb
F - mvb
G - hvb

IFRF

Fig: 53 .Burnout as a function of atomizing air rate for the 7 slurries FC = ¾ . Tsec = 300 °C

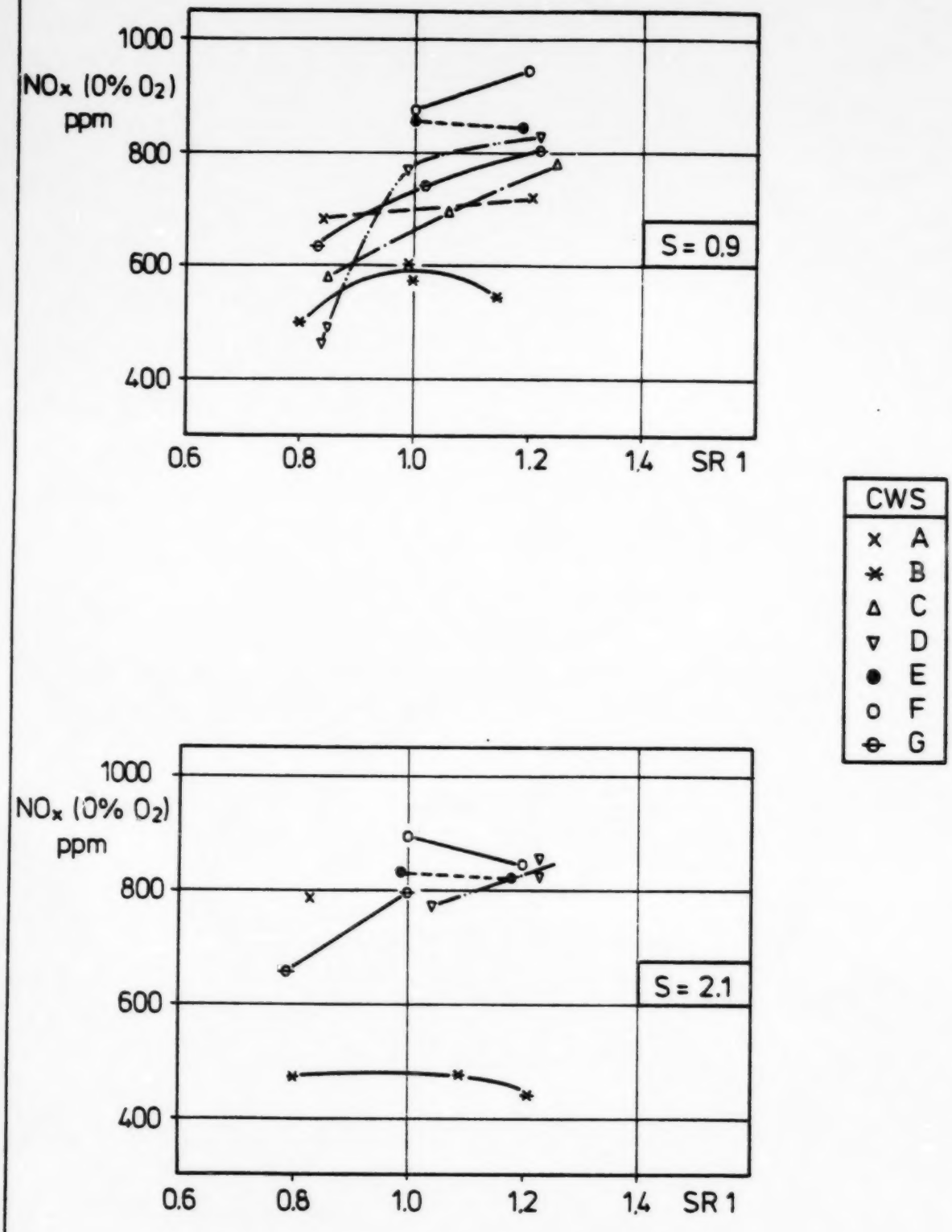
slurry type

A	mvb	E	hvb
B	lvb	F	hvb
C	hvb	G	hvb
D	hvb		



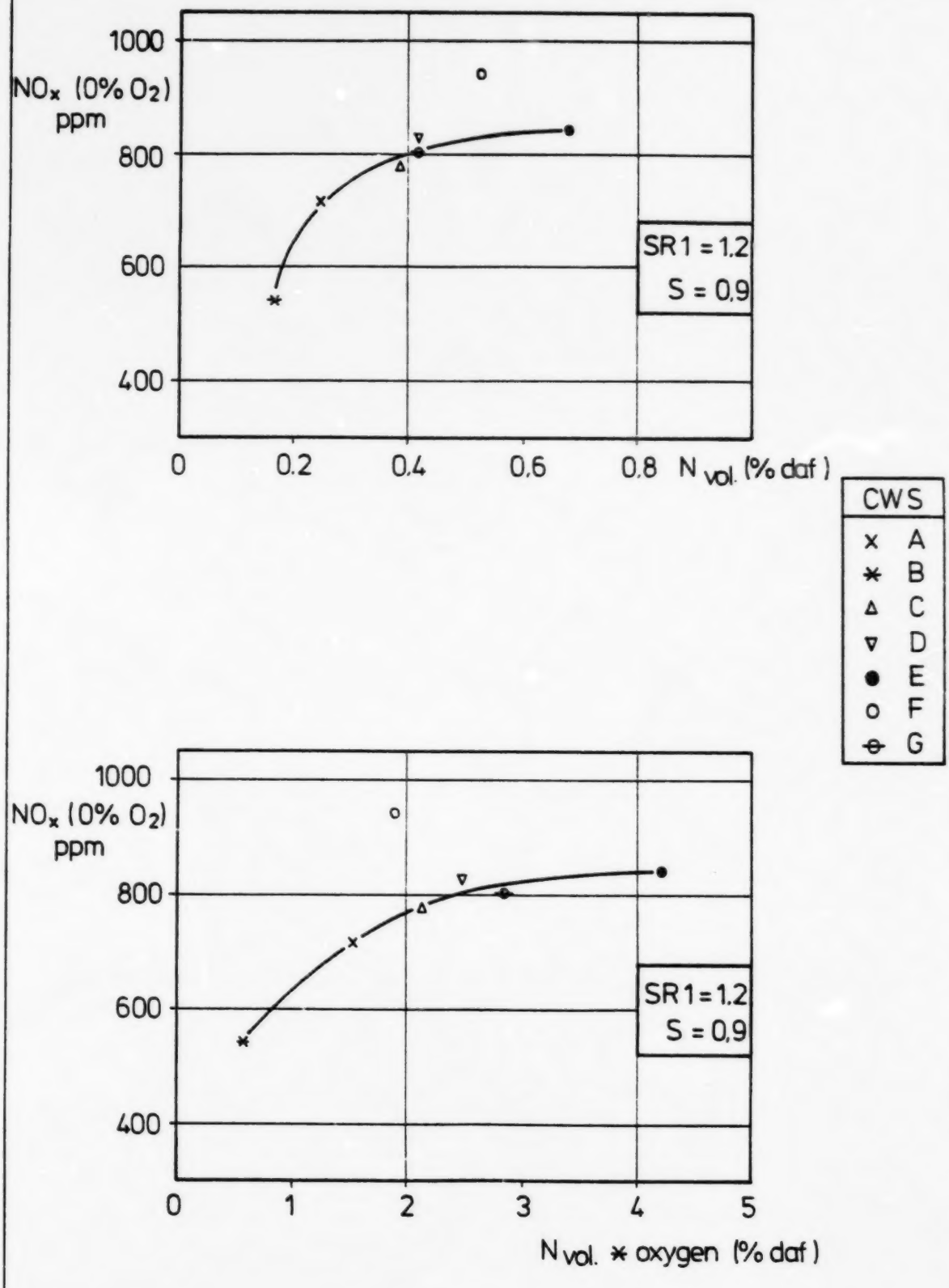
IFRF

Fig: 54 Minimum atomizing air rate required for good combustion versus apparent viscosity



IFRF

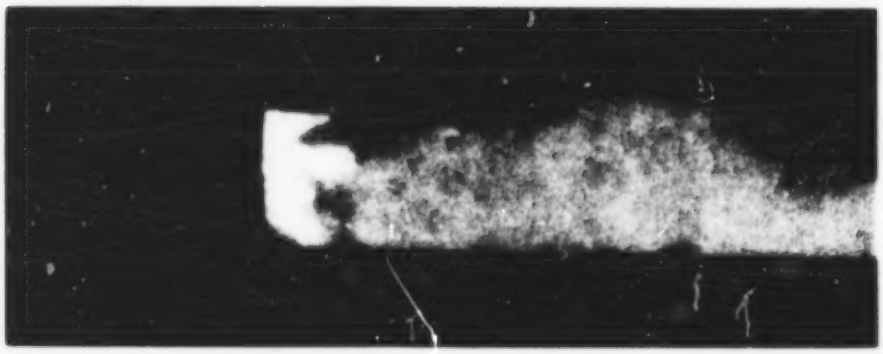
Fig: 55 NOx emissions versus primary zone stoichiometry



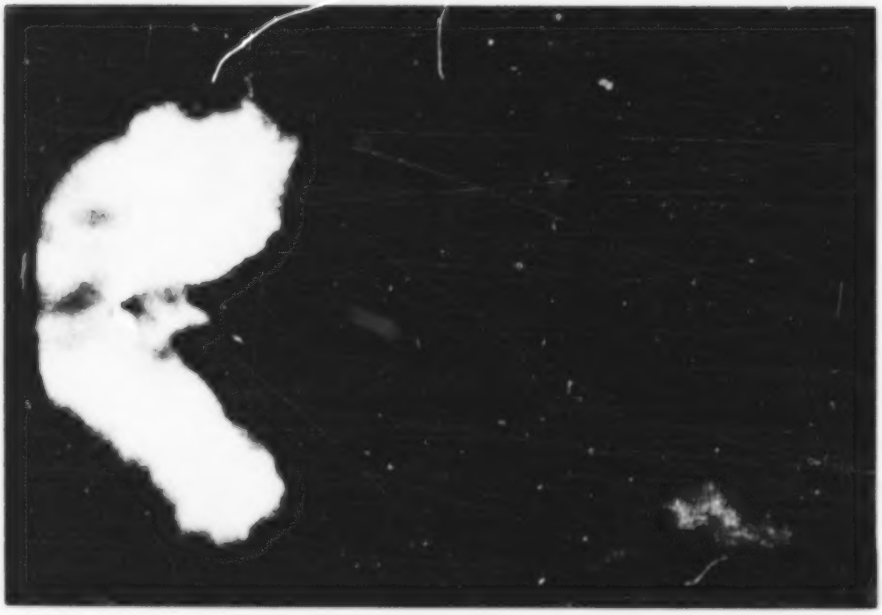
IFRF

Fig: 56 NOx emissions versus coal properties

PHOTOGRAPHS



Photograph 1
Flame HL-234-5
CWS-U: 2.3 MW
Atm : Cl-d
AFR : 14.5%



Photograph 2
Flame HL-234-1
CWS-U: 2.1 MW
Atm : Cl-d
AFR : 14%

Photograph 3
Flame HL-234-6
CWS-U: 2.2 MW
Atm : CY-d
AFR : 19%
View : Chimney